Vol. XCII. No. 5. September–October, 1955

GEOLOGICAL MAGAZINE

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STEPHEN AUSTIN & SONS, LTD.
CAXTON HILL, WARE ROAD, HERTFORD, HERTS

SUBSCRIPTION 40/- PER ANNUM

GEOLOGICAL MAGAZINE

founded in 1864

by the late Dr. H. Woodward, F.R.S., with which

is incorporated

THE GEOLOGIST

(founded 1858)

Published every two months, price 40/- per annum
(single numbers, 8/6).

Subscriptions for 1955, inquiries relating to back stock, advertising, etc., should be sent to Stephen Austin & Sons, Ltd., Caxton Hill, Ware Road, Hertford, Herts.

The Editors are directed to make it known to the public that the authors alone are responsible for the facts and opinions contained in their respective papers and for the correctness of their references.

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GEOLOGICAL MAGAZINE

VOL. XCII. No. 5. SEPTEMBER–OCTOBER, 1955

Issued 24th October, 1955

The Ben Lui Recumbent Syncline (S.W. Highlands)

By W. A. CUMMINS and R. M. SHACKLETON

ABSTRACT

Structural evidence from the Ben Lui district supports Bailey's view that the hinge of a major recumbent fold can be demonstrated there. Way up evidence indicates that all the recumbent structures from the Ben Udlaidh fold upwards face towards the south-east and south-south-east. The Ben Udlaidh and Ben Lui folds are therefore synclines. The attitude and character of the folds suggest gravitational flow.

STRUCTURES IN THE BEN LUI BLOCK

THE Ben Lui recumbent fold is an important element in the current interpretation of Scottish Dalradian structures, for it is the hinge connecting the downward-facing [1] succession of the Loch Tay flat belt with the upward facing succession of the belt to the north-west. Bailey, to whom this interpretation is mainly due (Bailey, 1922), claims that the Ben Lui fold is clearly exposed on Ben Lui. In a recent paper in this journal, however, Gilmour and McIntyre (1954) conclude that present knowledge is opposed to the view that a major recumbent fold exists in the Ben Lui region ; the supposed hinge " is merely the crest of an antiform ". This conclusion is reached from consideration of a profile, constructed from the published maps, using the plunges of minor structures recorded by McIntyre.

Our own work in the area, mostly done before Gilmour and McIntyre published, does not support their conclusions although we can confirm much of the observational evidence on which those conclusions were based. On Ben Lui it is the attitude of the strata forming the northern limb of the Ben Lui fold and outcropping along the north side of the range which is in question.

[1] A bed or succession is said to *face* towards the side which was originally the top (Shrock, 1948). Extending this term to structures, we say that a fold faces in the direction, normal to its axis and in its axial plane, in which younger beds are met. Beds intersected by a cleavage or schistosity are said to *face* along such a structure, normal to the intersection, towards the younger beds.

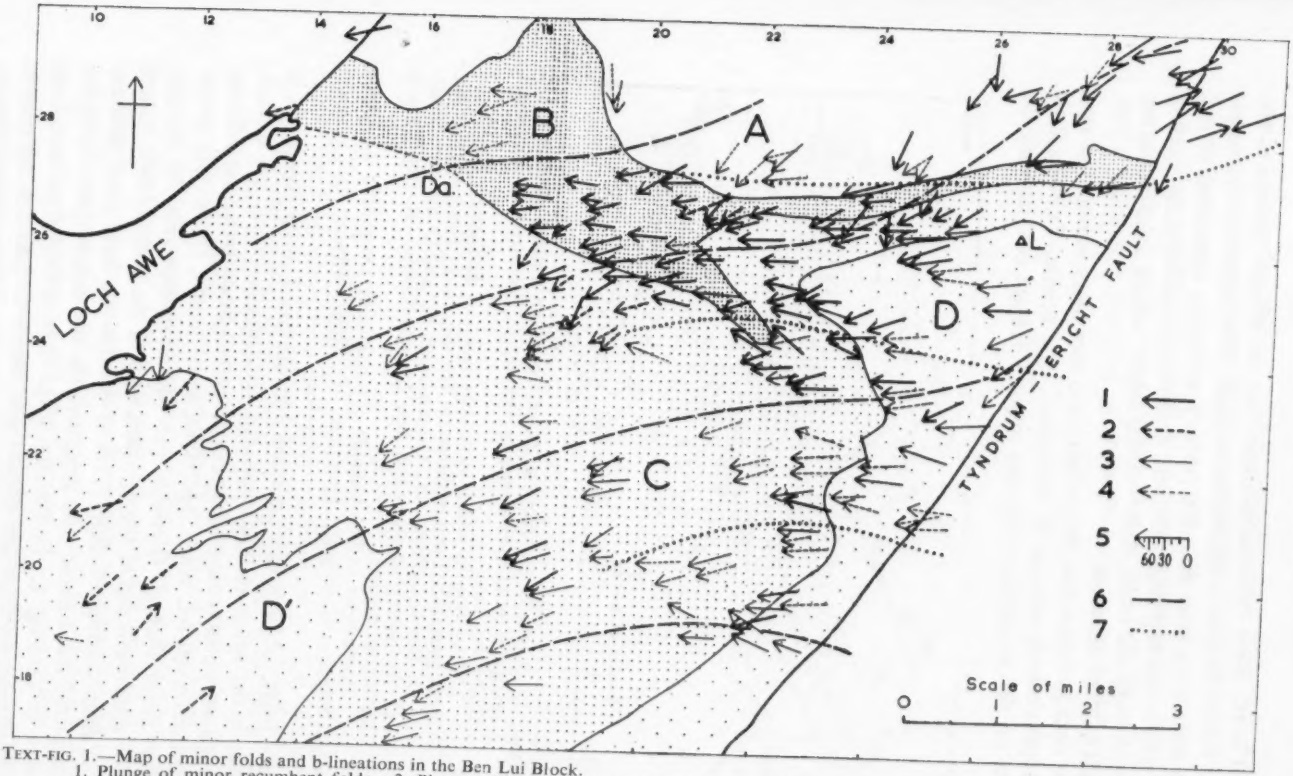
These strata are :—

3. Ben Lui garnetiferous schists.
2. Ben Lawers calcareous schists.
1. Ben Eagach graphitic schists.

To most geologists it will surely seem obvious even from the main road (A 85) west of Tyndrum, that the rocks along the north side of the Ben Lui range dip regularly southwards, as Bailey's section indicates. In the profile constructed by Gilmour and McIntyre, however, the contacts projected from that area dip northwards. The contacts trend 260° for some 3 miles west of the Tyndrum–Ericht fault (see Text-fig. 1). Their generalized dips may be calculated from the plunge of the minor folds if these are congruent with the major folds. A plunge towards 260° would imply that the contacts which trend 260° are vertical. The westerly plunge assumed by Gilmour and McIntyre implies a northward dip, while if the direction of plunge is south of 260° the dip is southwards as claimed by Bailey. It is surprising to find that Gilmour and McIntyre record no observations from the area in question north, north-west, or west of Ben Lui. Instead they extrapolate across this critical area from data obtained elsewhere. Our data from this area do not support the generalized trend line which they used to construct a " corrected profile ". We find that the plunges of the minor folds imply a southerly dip.

The minor structures whose attitude we have measured in the Ben Lui area (see Text-fig. 1) are of various kinds. The rocks of the area show structures recording at least two superimposed phases of deformation. Here we shall refer to these two sets of structures as primary and secondary. In exposures which show both, their distinction is simple, and in general they are so unlike that their separation is easy. The primary structures we have mapped are folds, flow-cleavage, schistosity, and lineations. The primary folds are usually tight or isoclinal, and are often flowage folds showing rapid changes of thickness of the beds. At high structural levels in the area they usually exhibit an axial plane schistosity or flow cleavage, while at deeper levels a bedding plane schistosity generally passes round the hinges of the minor folds. Primary lineations parallel to the axes of these folds include intersections of bedding with schistosity, well developed fold mullions (Wilson, 1953) in the Ben Lui Schists, and small-scale crinkling of the schistosity. Sections were made of a specimen of garnetiferous mica schist (233249) [1] with crinkled schistosity. The arrangement of inclusions in the garnets indicates rotation about an axis parallel to the lineation. A few crystals were rotated during growth, but most were

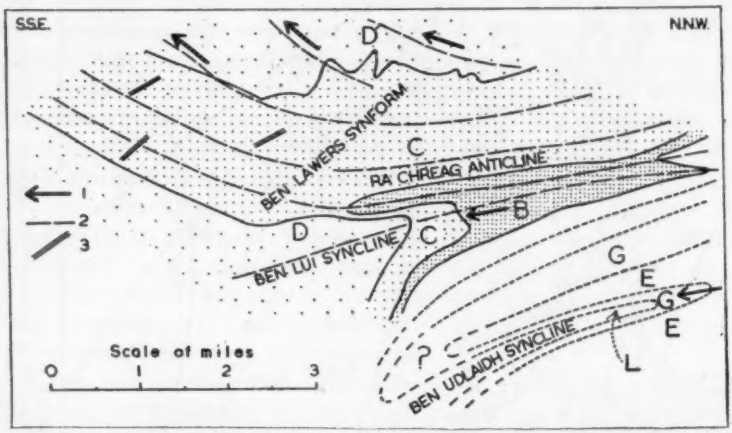
[1] Figures in brackets are national grid references to localities on Sheet 61 of the " Popular Edition " one inch map of Scotland.



TEXT-FIG. 1.—Map of minor folds and b-lineations in the Ben Lui Block.
1. Plunge of minor recumbent folds. 2. Plunge of intersection of bedding with schistosity. 3. Plunge of secondary minor folds. 4. Plunge of other and undifferentiated b-lineations. 5. Stereographic scale used to show angle of plunge by length of arrow. 6. Generalized trend lines of folds and b-lineations. 7. Generalized trend lines of folds and b-lineations according to Gilmour and McIntyre (op. cit., fig. 2).
A. Rocks older than Ben Eagach schists. B. Ben Eagach schists. C. Ardrishaig phyllites and Ben Lawers schists. D. Ben Lui schists, supposedly equivalent to D', Grinan Grits. L. Ben Lui. Da. Dalmally. National Grid references at margin.

rotated later. Such evidence indicates that the primary structures are closely related in time to the metamorphism. The secondary structures, which are clearly later than the primary structures mentioned above, are fracture- and slip-cleavages, seen as close-set parallel planes cutting evenly through the rocks, and " similar folds " whose axial planes are parallel to these cleavages.

Our data indicates that the primary and secondary minor fold axes are approximately coaxial in this area. The profile, Text-fig. 2, is drawn on the assumption that the major folds are coaxial with the



TEXT-FIG. 2.—Profile of the Ben Lui block, based on a mean plunge of 15° along the trend lines shown in Text-fig. 1. Vertical and horizontal scales the same.

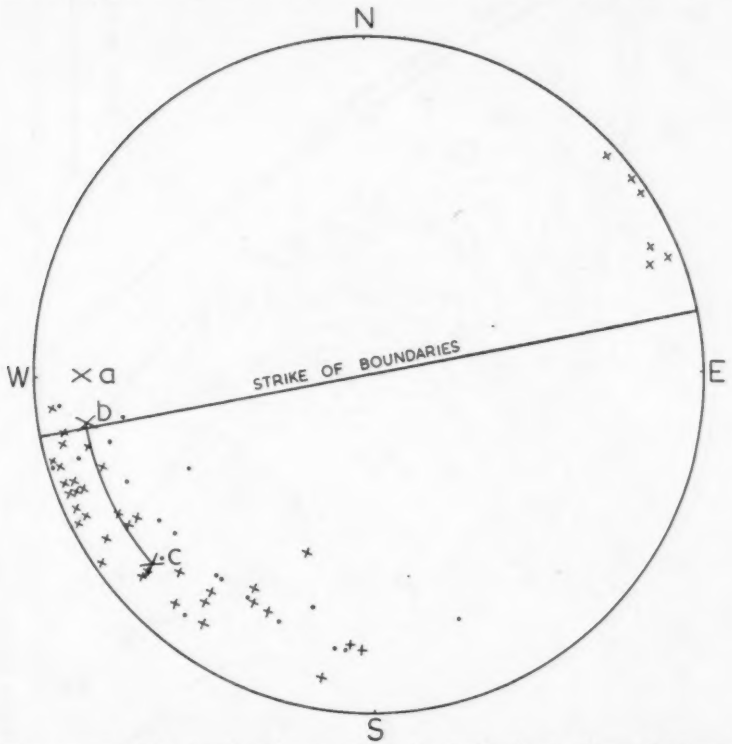
1. Direction in which structures face. 2. Schistosity (projected from generalized strikes shown on Text-fig. 5). 3. Fracture cleavage. D. Ben Lui schists. D′. Crinan Grits. (D and D′ are correlated). C. Ardrishaig Phyllites and Ben Lawers Schists. B. Ben Eagach graphitic Schists.

Formations in Ben Udlaidh syncline (diagrammatic): L. Leven Schists. G. Glencoe Quartzite. E. Eilde Flags.

minor folds. It is further assumed that the trend of the structures in depth is the same as that measured vertically above at the surface, though more detailed study may reveal systematic differences at different structural levels (cf. Weiss, McIntyre, and Kürsten, 1955). Our profile differs from that of Gilmour and McIntyre especially in showing a low southward dip of the northern limb of the Ben Lui fold instead of a steep northward dip. This is because we have used different generalized trend lines. The data, and the two sets of trend lines, are shown in Text-fig. 1. In Text-fig. 3 the axes of primary minor folds and b-lineations from the critical area north of Ben Lui are plotted on an equal area net. It is clear from this diagram that Gilmour

and MacIntyre's assumed westerly plunge is not consistent with the data, and their conclusion that the beds dip northwards is not supported by any evidence.

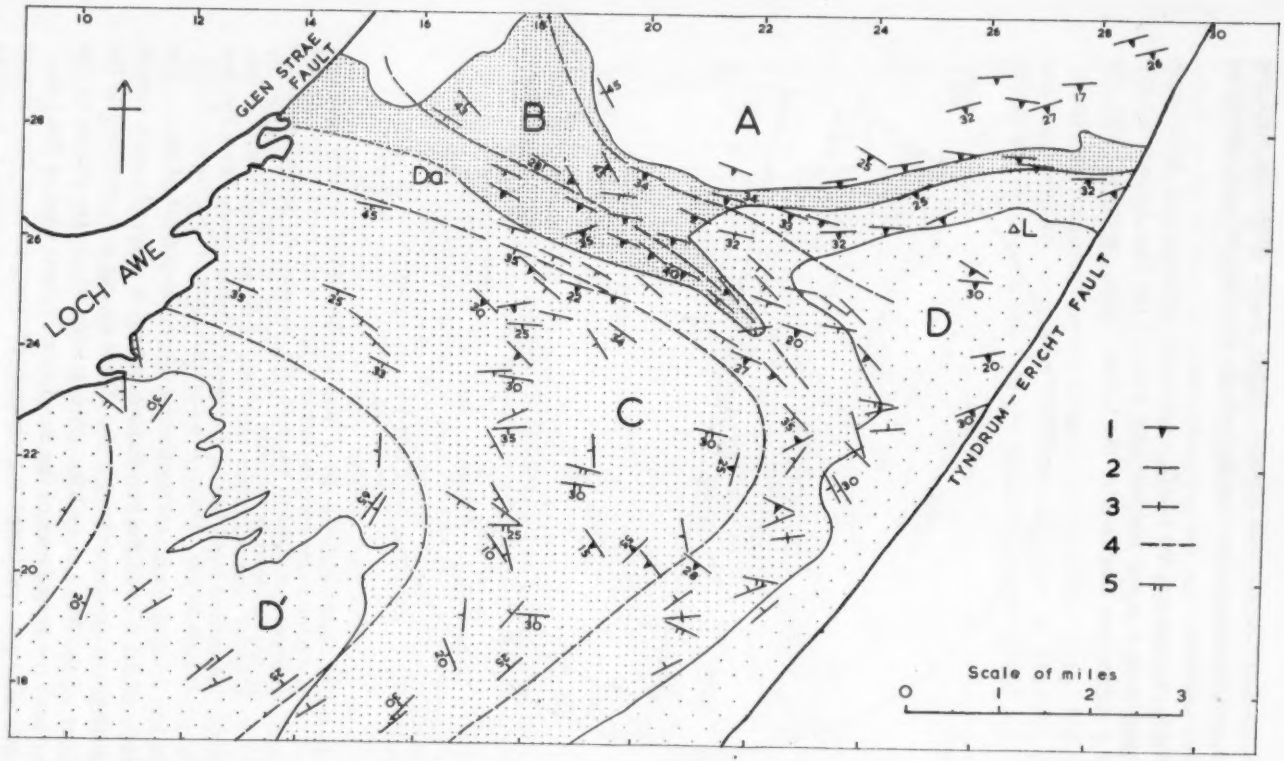
We have extended the profile structurally upwards and downwards by projecting a lower horizon (the base of the Ben Eagach schists) and a higher one (the base of the Crinan Grits, correlated with the



TEXT-FIG. 3.—Plot (equiareal net; lower hemisphere) of primary fold axes and b-lineations from the northern limb of the Ben Lui fold (east of national grid 220 and north of 260), showing the generalized strike of the mapped boundaries, the average plunge (*a*) assumed by Gilmour and McIntyre (op. cit.), and the range (*b–c*) of our generalized trend line in this area. Crosses: beds below the Ben Eagach Schists. Dots: Ben Eagach Schists and Ben Lawers Schists.

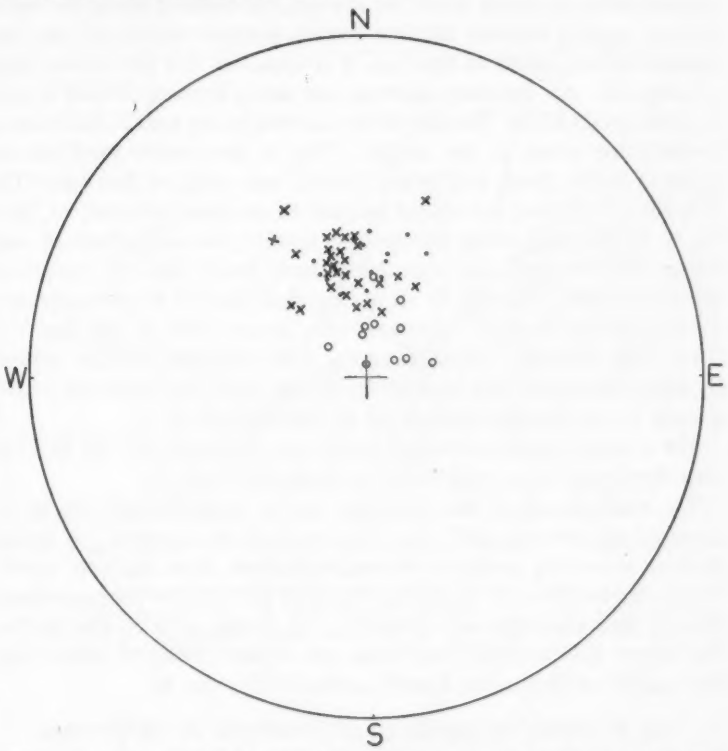
Ben Lui Schists), again taking the lines from the published maps. The profile of the base of the Ben Eagach Schists is of interest as it reveals the hinges of two recumbent folds. These appear to correspond to the hinges of the Ben Lui and Ra Chreag folds which are shown by the profile of the boundaries of the Ben Lawers schists west of Ben Lui.

We have also projected the generalized trend lines of the primary schistosity (shown in Text-fig. 4) on to the profile, Text-fig. 2. It will be



TEXT-FIG. 4.—Map of planar structures in the Ben Lui block.
1. Bedding. 2. Schistosity or flow cleavage. 3. Ditto, vertical. 4. Generalized strike of schistosity and flow cleavage. 5. Fracture cleavage.
A, B, C, D, D', and Da and L, as in Text-fig. 1.

seen that in profile the schistosity is parallel to the axial surfaces of the major folds which are found by projecting the mapped boundaries. On the map (Text-fig. 4) the generalized trend lines of flow cleavage and schistosity indicate the strike of the axial surfaces of the major folds ; we have insufficient data to trace the Ra Chreag fold through the Ardrishaig Phyllites.



TEXT-FIG. 5.—Plot of poles of bedding planes and axial planes of minor folds from the northern limb of the Ben Lui fold (data from same belt as Text-fig. 3). Crosses: bedding planes from below the Ben Eagach Schists. Dots: bedding planes in Ben Eagach and Ben Lawers Schists. Circles: axial planes of minor folds. Equal area projection, lower hemisphere.

The attitude and form of the primary major folds can be deduced not merely from a profile but also from the attitude and shape of the primary minor folds. Throughout the district the axial planes of the primary minor folds are inclined at low angles. Many of these folds are nearly isoclinal recumbent folds. One can traverse Ben Lui or Glen Orchy, and constantly see replicas on a small scale of the major recumbent folds which Bailey deduced from the geometry of the

outcrops. It is noticeable too, that at the hinges of the primary major folds there is unusually intense recumbent minor folding and strong b-lineation.

Further evidence of the attitude of the strata north of Ben Lui can be obtained by mapping the contacts across the rugged topography and by measuring the dip of the beds. To map the contacts accurately an instrumental survey would be needed, but walking along the easily located contact between the Ben Eagach graphitic schist and the Ben Lawers schists, north of Ben Lui, it is apparent that the contact dips southwards. An exposure showing this gently dipping contact is seen in a stream (268275). The dip of the bedding in this area is consistently towards the south at low angles. This is particularly clear on the crags of Beinn Dubh and Beinn Chuirn, just north of Ben Lui. The dips measured there are shown plotted on an equal area net, in Text-fig. 5. In this area, where the dip is so regular, the axial planes of such minor folds as were seen were consistently flatter than the prevailing dip of the beds (Text-fig. 5). It is thus clear that all these moderately dipping beds belong to one limb—the lower limb of the Ben Lui fold. The evidence is not consistent with repeated isoclinal folding by which the observed low southward dips could be combined to give a steep northward generalized dip of the formations.

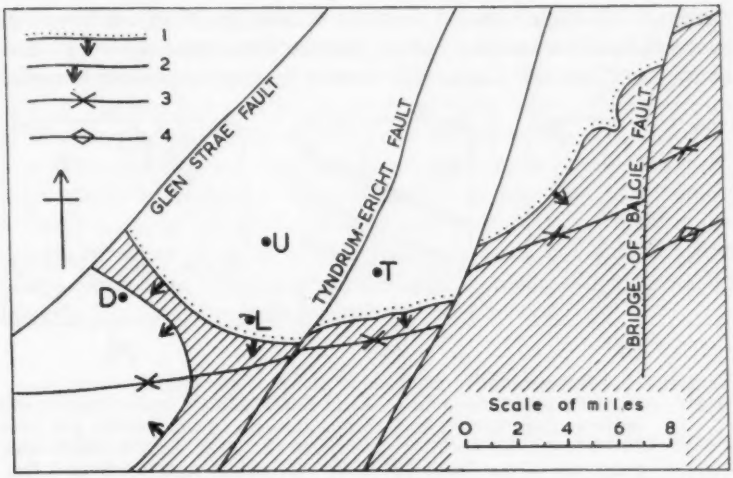
These several lines of evidence leave us in no doubt that the Ben Lui recumbent fold exists essentially as Bailey claimed.

The axial planes of the secondary minor folds are not parallel to those of the primary folds but dip regularly southwards. A major shallow secondary synform whose axial plane dips similarly southwards is revealed on the map (Text-fig. 5) by the curve of the generalized lines of flow cleavage and schistosity. It is also seen on the profile. We follow Bailey (1922) and Elles and Tilley (1930) in identifying this synform with the Ben Lawers synform (Text-fig. 6).

The Relation of the Ben Lui Structure to Structures exposed farther East

An important part of Gilmour and McIntyre's paper is concerned with the relation of the Ben Lui block to areas farther east. Again on the basis of the plunge of minor structures these authors project the well-known Loch Tay antiform for some miles across country ; it fetches up just beneath the Ben Lui fold. Thus they claim to have shown that these two structures are homologous and that the rocks of the flat belt involved in the Loch Tay antiform cannot represent the upper limb of the Ben Lui recumbent fold. We are unconvinced by this reasoning. Between Loch Tay and Ben Lui are three major faults currently regarded as sinistral strike-slip faults (Kennedy, 1946) by which the structures are wrenched several miles (see Text-fig. 6).

The effect of allowing for the wrenches on these faults when constructing a profile is that the Loch Tay antiform is projected several miles south of the Ben Lui hinge in the upper limb of the fold. Moreover, Gilmour and McIntyre's interpretation implies that the rocks of the " Loch Tay flat belt " are right way up, whereas it may easily be demonstrated that they are inverted. Evidence for this statement will be published separately.



TEXT-FIG. 6.—Sketch map to show the supposed relation of structures in the Ben Lui block to those farther east.

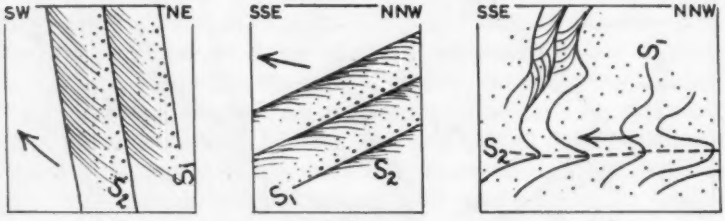
Outcrops of axial surfaces of folds: 1. Ben Lui syncline. 2. Ra Chreag anticline. 3. Ben Lawers synform. 4. Loch Tay antiform. The lined area represents the upper (inverted) limb of the Ben Lui syncline and the Loch Tay inversion (" flat belt ").

SENSE OF MOVEMENT OF THE RECUMBENT FOLDS

The sense of movement (of upper relative to lower levels) may be deduced from the direction towards which the folds face. This we have determined at a number of localities ; representative data are projected on the profile (Text-fig. 2).

Way up evidence is most easily available in the Crinan Grits at the highest levels of the structures shown in the profile. In many places graded bedding in these grits shows that they face upwards towards the south-south-east along the primary flow cleavage (Text-fig. 7 (*a*)). At a deeper structural level, in several grit bands exposed in the river bank west of Socach (especially at 204266 and 209265) graded bedding is seen, which shows that the beds face towards the south-south-east along the recumbent schistosity (Text-fig. 7 (*b*)). At a still deeper

structural level, near the hinge of the Ben Udlaidh fold in Glen Orchy (Bailey and MacGregor, 1912) way up evidence again indicates that the primary recumbent folds face south-eastwards. Spectacular exposures alongside the River Orchy show flat recumbent folds (especially at about 246330) and a little farther upstream (247330), in the left bank, an exposure shows quartzite folded into cylindrical and recumbent folds with strong b-lineation : these folds evidently belong to the same series as the larger recumbent folds just downstream. Through about 8 feet the folded quartzite exhibits well-preserved current bedding, whose attitude shows that these folds face south-east (Text-fig. 7 (*c*)). The intense folding hereabouts is typical



TEXT-FIG. 7.—Representative evidence of sense of movement.
(*a*) Graded Crinan Grits. Grid Ref. 126180. Graded units at this locality range from 1 to 9 feet in thickness. (*b*) Graded grit beds 2 to 3 feet in thickness. Near Socach (204266). (*c*) Current-bedded quartzite. Glen Orchy (247330). Height of section about 3 feet. S_1 = bedding; S_2 = schistosity in (*a*) and (*b*) and axial plane of recumbent folds in (*c*).

of the hinge-zones of the major folds. We have diagrammatically projected the Ben Udlaidh fold on to the profile (Text-fig. 2) to show its approximate structural relation to the Ben Lui fold. It follows from the way up evidence just given, that the Ben Udlaidh fold is a recumbent syncline, facing towards the south-east. The structure between the Ben Udlaidh and Ben Lui folds is not clear.

Thus the sense of the movements, wherever directly proved, throughout the structures shown on the profile is towards the south or south-east. This is not, we think, consistent with Bailey's eddy interpretation (Bailey, 1938) in which, if we understand it correctly, at the deeper levels, in the Ballapel foundation and on the Ballachulish lag, the movement was north-westwards, while at higher levels it was in the opposite direction.

INTERPRETATION

The form of the folds shown on the profile presents several features of interest. To us the most striking features are first the recumbency of the folds (the axial plane of the Ben Lui fold is inclined slightly

downwards in the direction of movement towards the south-south-east throughout our profile) ; secondly the drastic changes in the thickness of formations, indicating flowage ; thirdly the enormous increase in amplitude of these folds as they are traced stratigraphically upwards. The magnitude of this increase is not fully apparent from our profile as the youngest horizons shown do not close within it. Indeed, the Ben Lui Schists (D) and Crinan Grits (D^1) are only doubtfully connected through a wide expanse of air. It appears from other work done by one of us (R. M. S.) that the flat belt, which represents the upper limb of the Ben Lui fold, extends almost to the Highland Border ; in formations still younger than those exposed on Ben Lui, the inverted limb of the Ben Lui fold has a width of many miles. The character of this recumbent folding, especially the downward slope in the direction of movement, the preservation of the inverted limb (de Sitter, 1954), the stratigraphically upward increase in amplitude, the absence of steep roots in the rear and the close connection with the metamorphism, seem to us to point to deep-reaching gravitational flow as the mechanism by which the vast inverted sheet which forms the flat belt was moved and the recumbent folds formed.

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Modal Composition of Two Facies of the Carnmenellis Granite

By F. Chayes

Abstract

Modal analyses of nine specimens of Ghosh's Type I and six specimens of his Type II Carnmenellis granite indicate that there is no significant difference between the average compositions of these two facies.

In a still incomplete study of the effect of coarseness on the analytical error of modal analysis I have for some time been using a specimen of the Carnmenellis granite as a working standard. When the work was well along I discovered, to my chagrin, that the granites of Carnmenellis had been carefully studied by P. K. Ghosh (1934) and that the particular specimen serving as a standard of " coarse " grain came from a site mapped by him as " medium-grained ". The basis of distinction between Ghosh's " medium-grained " Type II and his normal " coarse granite " (Type I) is not very clearly stated. As far as grain size itself is concerned, it seems to be largely a matter of the relative abundance of feldspar insets. There is no mention of differences in size either of the insets themselves or of the constituents of the matrix in which they are set. There are evidently other rather subtle differences between the two facies, however, and Ghosh felt sure enough of his ability to distinguish between them to draw up a rather detailed map showing their areal distribution (1934, Fig. 1).

During a very brief visit to the Carnmenellis area I noted, of course, that the grain size of the granite was somewhat variable, but got no impression that this variation was at all systematic. After reviewing my field notes and examining my specimens rather carefully I am still rather sceptical of the possibility.[1]

Under the circumstances it seemed best to leave the subdivision of the specimens in other hands. W. S. MacKenzie of this Laboratory was kind enough to undertake it. He was told only that the specimens came from an area in which two facies had been distinguished by grain size, and he was asked to separate them into two groups on that basis. As nearly as we can make out, his groupings agree exactly with Ghosh's map; his " coarser " specimens all come from sites lying in Ghosh's Type I area, and his " finer " specimens are all from Ghosh's Type II. This is about as nice a confirmation of Ghosh's mapping as could be desired; unfortunately, the collection covers only the southeastern quarter of the Carnmenellis mass.

[1] Most of my specimens were collected in the active quarrying area. A large number of the quarries lie very near Ghosh's boundary, which I must have crossed several times in the course of collecting; perhaps this is the source of my scepticism.

The modal composition of the two facies is as shown in Table 1. From the standard errors given there it is evident that none of the differences between essential minerals is significant. This is not what would be expected from Ghosh's description. He says, for instance, that " . . . biotite is the dominant mica . . ." in Type I, while " . . . total muscovite is in excess of biotite . . ." in Type II. He adds that " . . . primary muscovite is reduced in Type II . . ." but if his " secondary " muscovite is sericite replacing plagioclase this does not resolve our difference. In my analyses " muscovite " does not include either sericite after plagioclase or fibrous, highly birefringent replace-

TABLE 1.—AVERAGE MODAL COMPOSITION OF TWO FACIES OF CARNMENELLIS GRANITE, VOLUME PER CENT.

Mineral	*TYPE I (Coarse)*		*TYPE II (Medium)*	
	Mean	*Standard error*	*Mean*	*Standard error*
Quartz	32·2	1·7	30·1	1·1
K-feldspar	30·5	2·0	30·4	1·4
Plagioclase	25·1	0·8	25·8	0·5
Biotite	5·3	0·4	5·7	0·3
Muscovite	5·6	0·5	6·4	0·4
Tourmaline	0·5	—	0·4	—
Andalusite	0·3	—	0·5	—
Opaque accessories	0·1	—	0·1	—
Non-opaque accessories	0·4	—	0·4	—
Color index (Shand)	12·2	—	13·5	—
Specimens	9		6	
Thin sections per specimen	2		4	
Measurement area per section	960 mm²			
Count length, average	1750			

ments of other minerals. The first has been included with plagioclase and the second with non-opaque accessories. In short, there seems to be little difference in the amount of either mica or in the total mica content in either facies.

Ghosh is also persuaded that the " . . . proportion of orthoclase relative to plagioclase " is larger in Type I and says that in Type II " plagioclase equals or may even exceed orthoclase in amount." There is certainly no evidence of this so far as the mean values shown in Table 1 are concerned. If Ghosh intended " may " here in the sense of " sometimes " the situation is still unchanged. Although 6 of the 24 individual thin section results for Type II show this relation, not one of the 6 specimen means does so. On the other hand, 5 of the individual thin section results for the Type I specimens indicate an excess

of plagioclase over potassium feldspar and this is true also of two of the 9 specimen means, though in one case the difference is a matter of 0·3 per cent. Fluctuations of this type are expectable in such coarse material and it is both surprising and encouraging that they did not appear in the specimen means for Type II.

Though there apparently is some perceptible difference in appearance as between the Carnmenellis Types I and II, the evidence presented here suggests that this has nothing to do with bulk or average modal composition. The two facies may not be absolutely identical in this respect but the differences between them must be trifling.

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A Clinopyroxene from the Granophyre of Meall Dearg, Skye

By Y. M. Anwar

Abstract

Chemical and optical data are presented for a ferrohedenbergite separated from the Tertiary Meall Dearg granophyre of Skye. Comparison is made with similar pyroxenes crystallizing in the later stages of the Skaergaard intrusion.

Introduction

ALTHOUGH pyroxene-bearing granites and granophyres are fairly common among the rocks of the British Tertiary igneous province, no chemical or optical data for the pyroxenes seems to be available. This note embodies the results of an investigation of the pyroxene contained in one of the two granophyres of Meall Dearg, Red Hills, Skye (Text.-fig. 1), first described by Harker (1904).

Petrography of the Pyroxene-Granophyre

The rock is medium-grained and greenish in colour in the hand-specimen, consisting of quartz, feldspar, olivine and its decomposition products, clinopyroxene, and iron ores, with accessory apatite, zircon, epidote, allanite, and fluorite.

The orthoclase is usually perthitic, often with rectangular outlines, and extending outwards in granophyric intergrowth with the quartz. The strongly-zoned plagioclase is on the average an oligoclase, An_{12-20}, sometimes enclosed by mantles of zoned potash feldspar. The olivine, when unaltered, is an amber-yellow, non-pleochroic ferrohortonolite, ($2V_\alpha$ 54°, corresponding to a composition Fa_{87}), but most of it has altered to a deep-green chloritic material.

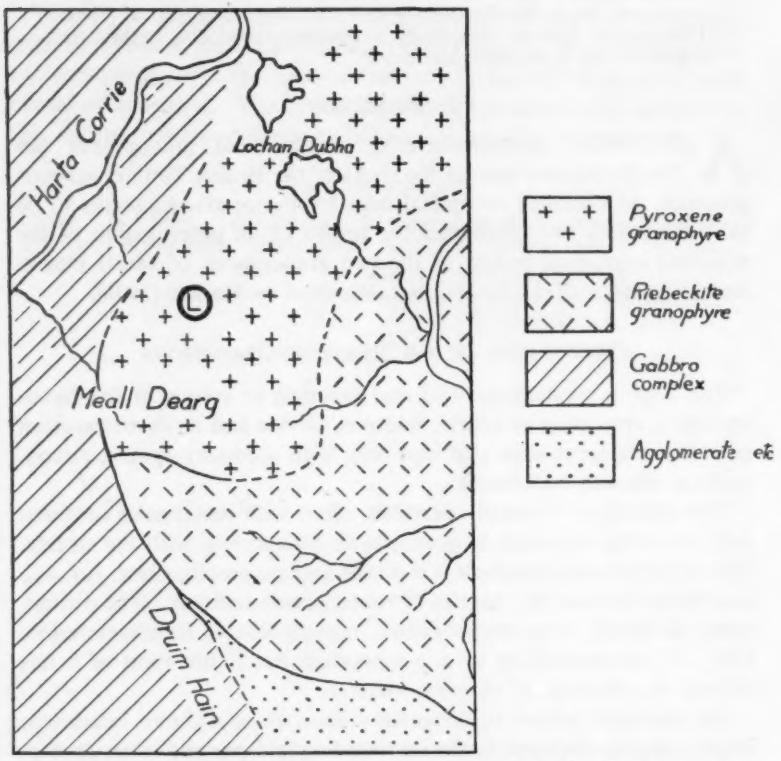
The pyroxene occurs as elongated prisms, about 1·5 mm. maximum length, usually embayed by the surrounding feldspar and often appearing as detached plates in optical continuity. The mineral is greenish and slightly pleochroic with $\gamma = \beta$ brownish-green; α green. It is occasionally altered, usually to a green chlorite but occasionally to a greenish amphibole. Exsolution lamellae are absent.

A chemical analysis of the granophyre is given in Table 1, together with certain others for comparison from the British Tertiary province. The mineral phases in the Meall Dearg granophyre are also remarkably similar to the basic hedenbergite granophyre, E.G. 3047 from the Skaergaard intrusion, but the analyses of the rocks show that the proportions of the minerals present are different.

The rock clearly belongs to the relatively silica-poor sub-group of the British Tertiary granites as divided by Harker and is fairly closely comparable with other pyroxene-granophyres from the region.

Chemical Composition and Optics of the Clinopyroxene

The material for chemical analysis was prepared by centrifuging the rock powder in heavy liquids and microscopic check indicated the presence of about 0·4 per cent impurities.



Text-fig. 1.—Geological sketch-map (based on Harker's 6-inch map) of Meall Dearg area, Skye. Ⓛ is the locality of analysed specimen.

The results of the analysis are given in Table 2, together with a distribution of the atomic proportions in accordance with the general structural formula for the pyroxenes, as proposed by Hess (1949).

A similar pyroxene sample was separated independently in the Department of Mineralogy and Petrology, Cambridge, from a specimen of the granophyre taken from a nearby locality. A chemical analysis of this sample, made by Mr. J. H. Scoon, with optical determinations by Dr. I. D. Muir, is also included in Table 2, by kind permission of Professor C. E. Tilley.

The mineral may be classed as a ferrohedenbergite, fairly low in sesquioxides and titania, but rather rich in manganese.

TABLE 1.—CHEMICAL ANALYSES OF PYROXENE-GRANOPHYRES

	A	1	2	3	4	5
SiO_2	69·24	73·32	73·12	71·30	68·42	71·68
Al_2O_3	12·25	12·25	12·44	11·24	13·54	12·55
Fe_2O_3	2·20	2·77	2·09	1·80	2·53	2·29
FeO	4·14	2·20	1·65	2·84	2·02	2·40
MgO	0·20	0·11	0·14	0·61	0·22	0·24
CaO	1·92	1·65	0·88	1·56	2·13	0·92
Na_2O	4·20	3·92	3·90	3·44	5·12	4·28
K_2O	4·27	2·34	4·67	4·66	4·08	4·37
H_2O^+	0·35	0·35	0·24	1·04	0·15	0·64
H_2O^-	0·23	0·35	0·25	0·39	0·25	0·25
TiO_2	0·50	0·51	0·39	0·58	0·81	0·38
P_2O_5	0·23	0·10	0·09	0·22	0·38	0·03
MnO	0·14	0·12	0·17	0·31	0·10	0·05
Total	99·87	99·99	100·03	99·99	99·75	100·08

C.I.P.W. Norm of Pyroxene-granophyre A

Quartz			23·4	
Orthoclase			25·2	
Albite			35·5	62·1
Anorthite			1·4	
Diopside	$CaSiO_3$	2·6		
	$MgSiO_3$	0·2	5·4	
	$FeSiO_3$	2·6		
Hypersthene	$MgSiO_3$	0·3		
	$FeSiO_3$	2·6	2·9	
Magnetite			3	
Ilmenite			0·9	
Apatite			0·5	

Mode of Pyroxene-granophyre A (*Vol. per cent*)

Quartz and micropegmatite	45
Orthoclase and perthite	28
Plagioclase	12
Pyroxene	5
Olivine, etc.	2
Iron ore and chlorite	8

A. Pyroxene-granophyre, (specimen no. 39) Meall Dearg, Skye. Anal.: Y. Anwar. (New analysis.)

1. Augite-granophyre. Knock Ring Dyke, Beinn Bheag, Mull. Anal.: E. G. Radley. (Mull Memoir, p. 20.)

2. Augite-granophyre, Beinn a Ghraig Ring Dyke, Mull. Anal.: E. G. Radley. (Mull Memoir, p. 20.)

3. Augite-granophyre, acid craignurite Cone Sheet, Craignure Bay, Mull. Anal.: E. G. Radley. (Mull Memoir, p. 20.)

4. Augite-granophyre, intrusion, S. 30° E. of Grigadale, Ardnamurchan. Anal.: B. E. Dixon. (Ardnamurchan Memoir, p. 84.)

5. Pyroxene-granite (G^2), water-worn gully on S.E. face of Beinn Dearg Mhor at c. 1,400 feet, Skye. Anal.: E. A. Vincent. (*Min. Mag.*, vol. 30, p. 270.)

The optic axial angle, 2V, and the extinction angle, $\gamma\Lambda c$, of the pyroxene were measured in thin sections on the universal stage, the latter by the method of Burri, as described by Haff (1941). The refractive indices were measured by the immersion method, in sodium light, the β index being determined in (100) parting tablets as described by Hess (1949).

TABLE 2.—CHEMICAL COMPOSITION AND OPTICAL PROPERTIES OF THE MEALL DEARG CLINOPYROXENE

Analysis by Y. M. Anwar.

Atomic proportions		Al	2Al	Al	Z	Cations to six oxygens
	Fe^{3+}	Fe^{3+}	Ti	Al	Y	
	Na				W	
Si . 772		7	16	$2\frac{1}{2}$	Z $797\frac{1}{2}$	1·97
Al . 28						
				$2\frac{1}{2}$		
Fe^{3+} . 25	18	7				
Fe^{2+} . 390						
Mn . 18					W, X, Y	
Mg . 45					$826\frac{1}{2}$	2·04
Ca . 320						
Na . 15	18					
K . 3						
Ti . 8			8			
O . 2,430						

SiO_2 .	46·56
Al_2O_3 .	1·42
Fe_2O_3 .	2·01
FeO .	28·05
MgO .	1·82
CaO .	17·96
Na_2O .	0·45
K_2O .	0·14
H_2O^+ .	0·17
H_2O^- .	0·04
TiO_2 .	0·60
MnO .	1·24
Total .	100·46

Sp. Gr. 3·58.

Composition (Atomic %): $Ca_{39\cdot4}$, $Mg_{5\cdot5}$, $Fe_{55\cdot1}$

Al in Z group: 3·2 per cent.

Optical properties: $\alpha = 1\cdot735$, $\beta = 1\cdot740$, $\gamma = 1\cdot765$ (all $\pm$ 0·002).*

$2V\gamma = 56° \pm 2°$, $\gamma\Lambda c = 47°$.

* The refractive indices were kindly redetermined by Mr. N. E. Butcher, using a single variation immersion technique.

Analysis by J. H. Scoon on a different Sample

SiO_2	.	46·86
Al_2O_3	.	1·31
Fe_2O_3	.	2·24
FeO	.	26·91
MgO	.	2·32
CaO	.	18·45
Na_2O	.	0·25
K_2O	.	0·20
H_2O^+	.	0·19
H_2O^-	.	0·24
TiO_2	.	0·57
MnO	.	0·83
Total	.	100·37

Composition (Atomic per cent): $Ca_{43\cdot9}$, $Mg_{7\cdot3}$, $Fe_{50\cdot8}$.
$\alpha = 1\cdot735$, $\beta = 1\cdot742$, $\gamma = 1\cdot764$. $2V\gamma = 53°$, $\gamma \wedge c = 47°$.
Pleochroism feeble, α = pale green, β and γ = brownish green.
Exsolution lamellae absent.

The values of 2V and β, when referred to the revised diagram given by Muir (1951, Fig. 4) correspond to a composition of Ca_{13} Mg_2 $Fe_{5?}$. This composition differs somewhat from the analytically determined value of Ca_{39} Mg_6 Fe_{55}, particularly in the proportion of Mg. The Meall Dearg pyroxene carries quite ordinary quantities of sesquioxides, titanium and alkalis, and none of these constituents would be expected to affect the optics appreciably.

The possible effect of the rather high manganese is not known. The excess of the total number of atoms in the W, X and Y groups in the analysis (Table 2) compared with the Z group may be largely due to the inclusions of opaque iron-ore in the analysed material.

Comparisons with Other Clinopyroxenes

In Table 3 the analysis of the Meall Dearg pyroxene is compared with rather similar ferrohedenbergites from the Skaergaard intrusion, and with certain others.

The Skaergaard pyroxene analyses 1–4 are of interest in that they represent late-stage members of the clinopyroxene series derived by fractional crystallization of a basaltic magma (Wager and Deer, 1939, p. 240–248; Muir, 1951). In this intrusion, two distinct trend-lines for these late pyroxenes have been established: the normal ferro-augites crystallizing directly from the magma below the β-wollastonite inversion temperature, and the other trend resulting from the β-wollastonite-hedenbergite inversion.

The Meall Dearg pyroxene lies on the trend of the normal pyroxenes which crystallized below the β-wollastonite inversion temperature, and very close to the plotted position of the Skaergaard pyroxene 3 (Muir

TABLE 3.—ANALYSES OF CLINOPYROXENES

	A	1	2	3	4	5	6	7
SiO_2	46·56	42·62	46·60	45·05	46·54	48·34	48·28	47·58
Al_2O_3	1·42	5·24	2·37	nil	5·77	0·30	1·45	1·16
Fe_2O_3	2·01	3·74	1·42	nil	1·88	1·50	3·96	2·60
FeO	28·05	31·54	29·70	31·76	24·65	22·94	27·02	24·21
MgO	1·82	0·47	0·67	1·35	0·79	1·06	0·32	3·34
CaO	17·96	12·27	16·01	19·09	17·70	21·30	16·18	18·80
Na_2O	0·45	1·02	0·73	0·73	0·62	0·14	1·51	0·47
K_2O	0·14	0·23	0·20	0·20	0·15	0·03	0·14	0·21
H_2O^+	0·17	0·48	0·43	0·43	0·39	0·46	0·15	0·34
H_2O^-	0·04	0·22	0·20	0·20	0·18	—	0·15	
TiO_2	0·60	1·69	0·75	0·55	1·22	0·08	0·28	0·37
MnO	1·24	0·78	0·92	0·64	0·74	3·70	0·76	0·59
Total	100·46	100·30	100·00	100·00	100·53	99·85	100·20	99·67
Sp. gr.	3·58	3·65	—	—	3·48			
α	1·725	1·743	1·745	1·745	1·726	1·723	1·736	1·730
β	1·732	1·751	—	—	1·732	1·730	1·745	1·736
γ	1·757	1·772	1·771	1·770	1·753	1·751	1·765	1·755
$2V\gamma$	56°	58°	52°	55°	49°	61–7°	70·25°	60°
$\gamma\Lambda c$	47°	47°	41°	—	44°	46–9°	56·5°(?)	47°

A. Ferrohedenbergite, Meall Dearg, Skye.

1. Ferrohedenbergite from fayalite-ferrogabbro, E.G. 1881. Skaergaard intrusion. Anal.: W. A. Deer. (Wager and Deer, 1939, pp. 77–8.)

2. } Ferrohedenbergite from fayalite-ferrogabbro, E.G. 4143. Compositions
3. } calculated from analysis of mixed pyroxenes. (Muir, 1951.)

4. Ferrohedenbergite from hedenbergite-andesinite, E.G. 4136. Skaergaard intrusion. Anal.: W. A. Deer. (Wager and Deer, 1939, pp. 77–8.)

5. Hedenbergite, Herault, California. Anal.: E. S. Shepherd. (Hess, 1949, p. 653).

6. Ferroaugite from quartz-syenite, Ausable Forks, N.Y. Anal.: L. C. Peck. (Hess, 1949, p. 654.)

7. Hedenbergite, Percy Quadrangle syenite, New Hampshire. Anal.: F. A. Gonyer. (Hess, 1949, p. 658.)

1951, Fig. 1; anal. 18). This latter occurs in the same rock as pyroxene 2, which was formed by inversion of β-wollastonite, the textures suggesting that pyroxene 3 crystallized only a little later than the wollastonite which inverted to give the pyroxene 2. The textural relationships of the iron-rich pyroxene of the Skye granophyre indicate that it is a primary mineral, able to crystallize from, and remaining in equilibrium with, a crystallizing acid magma.

ACKNOWLEDGMENTS

The author is indebted to Professor L. R. Wager for his guidance and advice; to Professor C. E. Tilley and Dr. I. D. Muir for making available to him their data on a similar mineral; and to Dr. E. A. Vincent for his help in preparing the paper.

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Phricodothyris in New South Wales

By K. S. W. Campbell

(PLATE XVIII)

Abstract

The relations of the genera *Torynifer* Hall and Clarke, *Phricodothyris* George, and *Kitakamithyris* Minato are discussed, and the diagnosis of *Phricodothyris* emended. The phricodothyrid species of New South Wales all bear dental lamellae and a median septum in the pedicle valve. Four new species from three horizons within the Carboniferous are described.

Introduction

THE reticulate spiriferids of New South Wales have never been studied systematically. The first reference to the group is that of McCoy (1847, p. 232), who referred the form described by Morris (1845, p. 279) as *Spirifer* (*Terebratula* ?) *crebristria* to the genus *Spirifera*, subgenus *Reticularia*. De Koninck apparently followed this lead, he being of the opinion that this species may be only a variety of *Spirifer lineatus* Martin. The type locality is described as Booral which is not sufficiently precise for the collector to be sure of collecting topotype material, since there are several Carboniferous fossil localities in the general vicinity. The holotype itself is (according to Dr. Maxwell, who kindly examined it on my behalf) a partly decorticated brachial valve with no indication of external ornament. Its true affinities seem to be impossible to determine. The problem will not be solved until extensive collecting is done in the Booral district and it is possible to compare this material with the type.

De Koninck (1877, p. 174) refers specimens from Buchan, " between the Karua River and Dungog, and Muree Quarry, Raymond Terrace," to *Spirifer lineatus* Martin. The two former localities are Carboniferous (probably in the Lower Burindi Group), but the latter is Permian. I have not had the opportunity of examining collections from any of these localities.

Dun (1902) remarks on the occurrence of a form, which he ascribes to *Reticularia lineata* Martin, in the Clarencetown district. From his locality on the Glen William Road, I have obtained a few isolated valves which are described later under *Phricodothyris uniplicata* sp. nov.

Subsequent to this work the only references to members of the group are in faunal lists, e.g. Carey (1937, pp. 352–3) and Voisey (1940, p. 209). All these occurrences are restricted to the Lower Burindi Group of sediments. (See Carey and Browne, 1938.)

No genuine *Reticularia* seems yet to have been discovered in the Carboniferous rocks of New South Wales.

PHRICODOTHYRIS George

Remarks.—The genus *Phricodothyris* was proposed by George (1932) to embrace reticulate spiriferids of brephomorphic shell form, surface ornamented with biramous barbed spines, and pedicle apical plates " usually absent but progressive, frequently attaining the primary, and sometimes the basilary stage (of Fredericks, 1927), but never the intermediate stage ". According to George (p. 540) the genus is most abundant in beds of Upper Viséan age, though it is possible that it occurs in the Lower Viséan and in the Millstone Grit. In Western Europe, *Phricodothyris* has been recorded by Demanet (1928) from the Upper Viséan of Belgium.

In 1894 Hall and Clarke proposed the name *Torynifer* for a form which Cooper (1942, p. 229) has recognized as a member of the species " *Reticularia* " *pseudolineata* (Hall). This species is strongly plicate, bears concentric lamellae with biramous spine bases, has strong special plates in the pedicle valve, and a ponderous concave hinge plate supported on a median septum in the brachial valve. The genotype occurs in the Keokuk limestone which is correlated with the uppermost Tournaisian of Europe. Cooper (1944) places " *Reticularia* " *setigera* (Hall) from the Chester (Viséan) Group into *Torynifer*, but gives neither figures nor description of the internal structure of the species. Stainbrook (1947) describes *T. spinosys* Kindle from the Percha Shale of New Mexico, a formation which he considers to be early Mississippian in age.

In the author's opinion the constancy of development of the hinge plate and strong median septum in the brachial valves of the American Mississippian reticulate spiriferids, and the absence of these structures from similar forms elsewhere indicates that *Torynifer* Hall and Clarke must be accepted as a distinct genus. Moreover, since it is found in the lowermost Mississippian, the lowest horizon on which reticulate spiriferids are known to occur, and it is not known to be associated with *Phricodothyris* in any of its areas of outcrop, the possibility must be conceded that its origin may be independent of that of the latter genus.

Minato (1951) proposed a new sub-genus *Kitakamithyris* of the genus *Torynifer* for forms which are similar to *Torynifer* in all characters except their lack of apical plates in the brachial valve. In the following year the same author raised *Kitakamithyris* to full generic rank, stating that it is " devoid of whatever kind of apical plates in the dorsal valve, in contradistinction to the presence of a median septum in the genus *Torynifer* ". The interpretation of his statements concerning brachial apical plates is difficult since some of his figures, e.g. (1952, pl. 6, fig. 5) appear to show crural supports and a faint depression in the position of the brachial median septum. It appears probable that all

Minato intends to convey is the absence of an entire concave hinge-plate supported on a strong median septum.

This genus appears to be closely related to *Phricodothyris* from which it differs in its plicate shell form, its strong median septum in the pedicle valve and its stronger and more constantly developed apical plates. In his original description of *Phricodothyris* George emphasized the intrageneric and intraspecific variability of the development of the pedicle apical plates, but in no description does he mention the presence of a pedicle median septum.

One of the species referred by Demanet (1938) to *Phricodothyris*, viz. *P. tripustulosa* Demanet, has " à la valve ventrale, lames apicales peu développées ; septum médian linéaire s'étendant sur les deux tiers de la longueur de la valve, traversant le champ musculaire allongé et étroit ". This is of particular interest since George apparently did not observe a median septum in any of his specimens. Thus even in the Viséan of Western Europe there appears to be some variation in the development of this structure. The English phricodothyrids are all either rectimarginate or only slightly sinuate, but the associated reticulariids are very variable in this character, ranging from slightly sinuate to parasulcate. *Kitakamithyris* appears to be variable in the form of the commissure but the extent of the variability is difficult to determine.

The species from New South Wales which are described hereunder exhibit variation from almost rectimarginate to strongly uniplicate. All these forms are also characterized by the presence of a strongly triseptate pedicle valve. It is also worthy of note that Prendergast (1935, p. 23) has described rectimarginate and plicate, triseptate forms referred to *Phricodothyris* from Fossil Cliff, Western Australia, a locality which is thought to be either Sakmarian or early Artinskian. Also from the Permian of Peru, Chronic (1953) records a phricodothyrid, *P. septata* Chronic, with a triseptate pedicle valve.

It is thus shown that reticulate spiriferids characterized by biramous spine bases exhibit a wide range of variation in the development of pedicle internal plates, including the median septum, and in the degree of plication of the commissure. The splitting of this apparently homogeneous group into separate genera is undesirable, and hence the diagnosis of *Phricodothyris* George, is here emended to include the above range of variation and *Kitakamithyris* Minato is regarded as a synonym.

In this interpretation of the genus the earliest known species, *P. triseptata* sp. nov. and *P. uniplicata* sp. nov. are triseptate, but are variable in the degree of plication of the commissure. Forms of this type continue through the Carboniferous into the Permian (Prendergast, 1935), but in Viséan and later times aseptate or feebly septate

forms were developed (Chao, 1929, p. 86, pl. viii, figs. 17–19 ; Cooper, 1944, p. 327 ; Muir-Wood, 1950, p. 52). It was from one such group of communities that the original description of the genus was prepared.

A note of caution should be added. I agree entirely with George (1932, p. 524) in his discussion of the English phricodothyrids, that to separate into two genera forms which differ only in the degree of the development of the dental lamellae " would postulate the development of this unique type of ornament in two unconnected groups of homeomorphs which lived together at the same time and in the same place—a rather improbable coincidence ". But since it has been shown to be possible that the genus *Torynifer* may have been developed independently of *Phricodothyris*, it is possible that biramous spines may have been developed at other times, and that *Phricodothyris* is polyphyletic.

Diagnosis.—Brachythyrid : commissure rectimarginate, uniplicate, or parasulcate ; surface ornament of concentric lamellae bearing biramous barbed spines ; shell structure fibrous, impunctate ; apical plates and median septum of the pedicle valve may be absent or exhibit variation in strength of development ; brachial valve without a concave hinge-plate and supporting median septum ; a very low, narrow median septum exists between and anterior to the brachial adductor scars.

Phricodothyris uniplicata sp. nov.

(Pl. XVIII, figs. 1–9)

? *Reticularia lineata* Martin in Dun, 1902, p. 85.

Holotype.—F. 1340, University of New England Collections.

Description.—The shell is transverse, averaging three-quarters as long as wide, with a hinge line three-quarters the width of the shell. The cardinal extremities are well rounded.

The pedicle valve has a high umbo, incurved towards the tip, and thus the cardinal area is high and concave. The greatest width of the valve is at approximately 7 or 8 mm. anterior to the hinge. The commissure is markedly uniplicate, and the median sinus extends to the umbo. There are between nine and fifteen concentric lamellae per 10 mm., and approximately sixteen to twenty spine bases per 5 mm. laterally on the median anterior portion of the valve. The concentric lamellae tend to become more closely spaced around the anterior and lateral margins.

The brachial valve is elliptical in outline, but it is very variable in length, causing considerable changes in its general appearance. The cardinal extremities are either sub-angular or rounded. The fold

is well defined, extends almost on to the umbo, and is very variable in height. The ornament is similar to that of the pedicle valve.

Internally the pedicle valve has strong dental lamellae which extend one-third of the length of the valve. They diverge at angles varying between 32° and 45°. The median septum is powerful and varies between one-half and two-thirds of the length of the valve. The muscle scars are very poorly defined.

The brachial valve is slightly thickened at the umbo. A faint median septum, which dies out almost imperceptibly about the mid length portion of the valve, is developed.

Dimensions.—The angle of divergence of the dental lamellae varies according to the position in which the specimen is held. All the measurements below have been made by holding the specimen with the commissure horizontal, and measuring the angle between vertically projected dental lamellae on a horizontal plane.

Pedicle Valves.

Length.	*Width.*	*Length of Hinge.*	*Height of Sinus.*	*Length of Median Septum.*	*Angle of Divergence of Apical Plates.*
24 mm.	34 mm.	22 mm.	—	—	—
31 „	36 „	22 „	7 mm.	—	—
26 „	33 „	19 „	3 „	14 mm.	32°
31 „	45 „	—	7 „	17 „	44°
26 „	32 „ ±	—	4 „ ±	—	—
28 „	38 „	23 „ ±	7 „	17 „	45°
—	—	20 „	—	17 „	45°

Brachial Valves.

Length.	*Width.*	*Height.*	*Height of Fold.*
26 mm.	40 mm.	9 mm.	6 mm.
28 „	41 „	7 „	5 „
24 „	32 „	6 „	4 „
33 „	44 „	12 „	10 „ ±
31 „	40 „	7 „	6 „
22 „	36 „	6 „	3 „

Remarks.—This form is not comparable with any overseas species with which I am acquainted.

Localities.—The type material is from the top of the lower Burindi Group at Babbinboon ; grid reference 570–637, Attunga one mile Military sheet ; L. 35, Univ. of New England Collections.

Two brachial valves (one exhibiting both internal and external moulds, and the other the internal mould only), and a fragment of the interior of a pedicle valve, have been found at Dun's locality on the Clarencetown–Glen William Road ; grid reference 803–730, Paterson one mile Military sheet. One cannot be sure that they are members of the species described by Dun (1902, p. 85), but the probability in favour

of this suggestion is high. The specimens are similar to *P. uniplicata* in all characters observable.

In this species are included eight rather poorly preserved specimens from the south bank of the Barrington River, north of Rawdon Vale Homestead on the Cobarkh Road. They appear to be identical with the specimens from the type locality.

Range.—The type locality and that on the Clarencetown–Glen William Road are both at the top of the Lower Burindi Group. The faunas at each locality are closely comparable and suggest an Upper Tournaisian age. Crockford (1951, p. 106) considers that the bryozoan faunas from the latter locality suggest " an age equivalent to an early part of the Osage Series in the United States, and so to an horizon within the upper part of the Tournaisian ".

The horizon of the specimens from near Rawdon Vale is unknown, but it is within the Lower Burindi Group and probably not far removed from that of the types.

Phricodothyris triseptata sp. nov.

(Pl. XVIII, figs. 10–15)

? *Seminula subtilita* Hall in Dun and Benson, 1920, pl. xxi, figs. 2, 3, 4.

Holotype.—F. 1322. University of New England Collections.

Description.—The shell is small in size, and is approximately four-fifths to six-sevenths as long as wide. The hinge line is short and the cardinal extremities rounded.

The pedicle valve is very convex towards the umbo, but is flatter anteriorly. The umbo is high, protuberant, and usually strongly incurved. The cardinal area strongly concave and finely striated at right angles to the hinge line. The hinge line is between two-fifths and one-half the greatest width of the shell. The umbonal ridges are angular. The venter is either gently rounded or flattened, or may bear a very slight sinus. The concentric lamellae are rather evenly spaced over most of the valve, there being six to eight lamellae on the median anterior portion of the valve, but they become more crowded on the extreme median and lateral portions. The biramous spine bases are arranged eight to nine per 5 mm. on the median portion of the valve.

The brachial valve is semi-elliptical in outline. It is variable in the degree of its convexity, but is most strongly convex towards the umbo. The ornament is similar to that of the pedicle valve.

Internally the pedicle valve has strong dental lamellae which extend approximately one-quarter the length of the valve. The median septum extends from the umbo to about the mid length of the valve, decreasing in both height and width anteriorly.

The umbo of the brachial valve is slightly thickened. A low median

septum arises in the umbo and extends one-third the length of the valve. The cardinal process is platy.

Dimensions.—

Pedicle Valves.

Length.	*Width.*	*Height.*	*Length of Hinge.*	*Length of Median Septum.*	*Angle of Divergence Dental Lamellae.*
23 mm.	28 mm.	9 mm.	—	—	37°
24 „	29 „	9½ „	—	16 mm.	37°
19½ „	26 „	6½ „	—	—	38°
21 „	26 „	7½ „	12 mm. (approx.)	—	—
30 „	36 „ (approx.)	—	—	18 mm.	37°

Brachial Valves.

Length.	*Width.*	*Height.*
18 mm.	23 mm.	4 mm.
21 „	30 „	6 „
20 „	27 „	6 „
17 „	26 „	5½ „
18 „	25 „	5 „

Remarks.—Of the British species *P. triseptata* most closely resembles the form described as *P. lineata* by George (1932), but there are marked differences in the septation of the pedicle valve and the density of the spine bases.

Locality.—The type material is from the top of the Lower Burindi Group at Babbinboon, L. 35, and to date no other material has been discovered.

Range.—Upper Tournaisian.

Phricodothyris rouchelensis sp. nov.

(Pl. XVIII, figs. 16–17)

Holotype.—F. 1382. University of New England Collections.

Description.—The shell is ovate in outline, approximately four-fifths as long as wide and has a hinge line about three-sevenths of the maximum width of the shell.

The pedicle umbo is very strongly incurved, and the cardinal area is almost semi-circular in a section taken through the umbo. A very faint narrow sulcus extends from a few millimetres anterior to the umbo to the anterior margin, which is slightly uniplicate. There are five or six concentric lamellae per 10 mm., and approximately seven spine bases per 5 mm. on the central portion of the valve.

The brachial valve has a prominent pointed umbo. Its length is approximately five-sixths of its breadth. A low fold is developed

on the anterior portion of the valve. The ornament has not been observed.

Internally the pedicle valve has rather slender dental lamellae approximately one-third the length of the valve. They are not quite straight but are slightly convex toward each other. The median septum is between one-half and two-thirds the length of the valve.

The brachial valve has a low median septum, thickened immediately beneath the umbo, and extending approximately half the length of the valve.

Remarks.—This species is similar to *P. triseptata* in size and conformation, but from that species it differs in its more widely spaced concentric lamellae and spine bases. Also all the specimens examined have a slight median sinus in the pedicle valve and a slight uniplication of the commissure, whereas *P. triseptata* rarely has a median sinus in the pedicle valve and where such does occur, it is broad and undulose, as opposed to the much narrower sinus of *P. rouchelensis.*

Locality.—Two hundred yards upstream from Cameron's Bridge, Rouchel Brook, in Pors. 1 and 34, Par. Rouchel, Co. Durham; L. 57, University of New England Collections.

Range.—According to Crockford (1947, p. 24) the marine beds at the above locality are " intercalated in the Lower Kuttung Series about 800 feet to 1,000 feet above its base ". The same author has described the bryozoan fauna from the locality and in her opinion it " shows no distinctive differences from the Lower Burindi fauna and is assumed to be of closely similar age " Crockford (1951, p. 106.) The Lower Burindi faunas she correlates with the Osagean and hence with the Upper Tournaisian.

In the opinion of the present author, the associated brachiopod fauna indicates that the bed may be of Viséan age, though insufficient work has been done to determine its exact zonal position.

Phricodothyris booralensis sp. nov.

(Pl. XVIII, figs. 18–19)

Holotype.—F. 1373. University of New England Collections.

Description.—The shell is large for the genus. It is ovate in outline, being approximately four-fifths as long as wide.

The pedicle umbo is apparently rather small, but strongly incurved. A shallow median sinus extends on to the umbo, the margins of the sinus being clearly but not sharply defined. The sinal angle approximates to 20°. The commissure is uniplicate. The concentric lamellae are rather closely set, there being twelve to fourteen per 10 mm. on the median anterior portion of the valve. There are ten to twelve spine bases per 5 mm. over the same region.

The brachial valve is ovate in outline, and is evenly convex in profile. A vertically striated cardinal area is well developed, and the median fold well defined.

The pedicle interior exhibits strong dental lamellae which in the largest specimen are slightly convex toward each other. Their angle of divergence is low—25°–30°, and they extend approximately one-third the length of the valve. The median septum is very powerful and extends three-fifths of the length of the valve.

The brachial valve is slightly thickened at the umbo, and from this thickening a median septum, which extends two-fifths of the length of the valve, arises. Short thick crural bases are developed.

Dimensions.—

	Length.	*Width.*	*Length of Median Septum.*
Pedicle Valve	42 mm.	58 mm.	26 mm.
Brachial Valve	30 mm.	48 mm.	12 mm.
	50 „	65 „	20 „

Remarks.—All the available material of this species is somewhat distorted or incomplete. It can be readily distinguished from all other forms by its size, its closely set lamellae, and spine bases, and the small angle of divergence of its dental plates.

Locality.—So far this species is known only from the quarry 2 miles east of Booral in the Gloucester trough where it is associated with a bryozoan–brachiopod fauna : L. 46, University of New England Collections.

Range.—The bryozoan fauna was described by Crockford (1949), and she regards it (1951, p. 109) as Upper Carboniferous in age, though she does not define her interpretation of that term. The associated brachiopod fauna contains the genera *Levipustula*, *Neospirifer*, *Spiriferellina*, and *Composita*, which assemblage suggests a Moscovian age.

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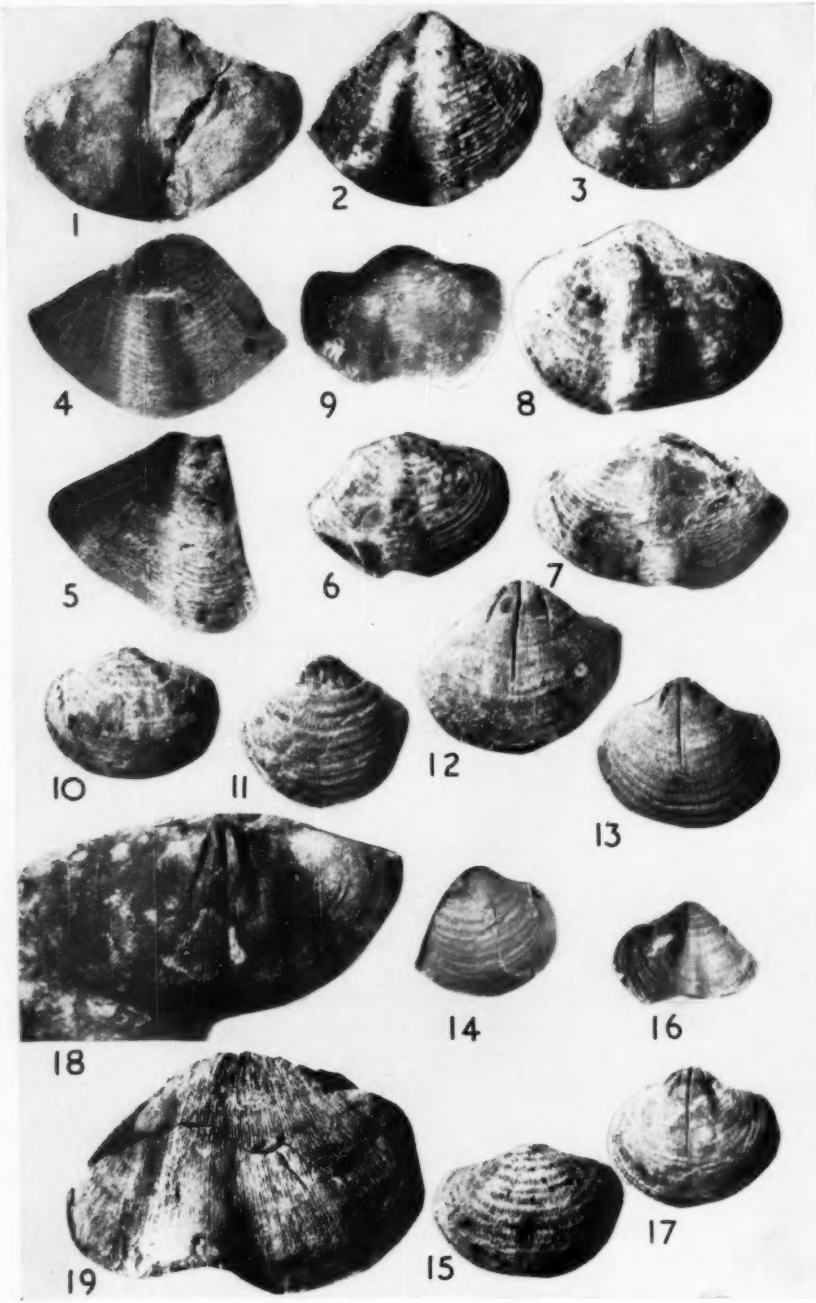

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EXPLANATION OF PLATE XVIII

All figures × 0·85. All specimen numbers refer to the University of New England Collections.

FIGS. 1–9.—*Phricodothyris uniplicata* sp. nov.

Figs. 1 and 5.—Internal and external moulds of pedicle valve; F. 1341; from Babbinboon, L. 35.

Figs. 2 and 4.—Partly decorticated pedicle valve with its external mould; F. 1340; Holotype; from Babbinboon, L. 35.

Fig. 3.—Internal of pedicle valve; F. 1342; from Babbinboon, L. 35.

Figs. 6–8.—Partly decorticated brachial valves; F. 1344, F. 1345, and F. 1343; all from Babbinboon, L. 35.

Fig. 9.—Brachial valve; F. 1366; from Clarencetown, L. 51.

FIGS. 10–15.—*Phricodothyris triseptata* sp. nov.

Fig. 10.—Brachial exterior; F. 1321; from Babbinboon, L. 35.

Figs. 11 and 14.—Pedicle valve and a cast of its external mould; Holotype; F. 1322; from Babbinboon, L. 35.

Figs. 12 and 13.—Internal moulds of pedicle valves; F. 1325 and F. 1323; from Babbinboon, L. 35.

Fig. 15.—Brachial valve; F. 1324 ; from Babbinboon, L. 35.

FIGS. 16 and 17.—*Phricodothyris rouchelensis* sp. nov.

External cast and internal mould of the Holotype; F. 1382; from Rouchel Brook, L. 57.

FIGS. 18 and 19.—*Phricodothyris booralensis* sp. nov.

Fig. 18.—Internal mould of a crushed pedicle valve, only the posterior portion being represented; Holotype; F. 1373; from 2 miles east of Booral, L.

Fig. 19.—Internal mould of a brachial valve; F. 1370; from 2 miles east of Booral, L.

A Note on the Mineralogy and Petrology of the Calciphyres near Nanjangud, Mysore, India [1]

By A. P. Subramaniam

Abstract

The calciphyres and granulites near Nanjangud in Mysore were examined in detail in view of the reported occurrence in them of a remarkable assemblage of rare minerals of the Sanidinite facies. A brief field examination disclosed the absence of Gabbro-limestone contacts previously reported. The calciphyres and calc-granulites occur as layers, lenses and nodules in a group of amphibolites and hornblende granulites. Thin sections of these granulites display cataclastic textures indicative of shearing, and crushing. They are found to be composed of minerals characteristic of high grade marbles, and the absence in them of such minerals as larnite, merwinite and spurrite recorded previously, is consistent with the present field observations.

Introduction

B. Rama Rao (1943) reported the occurrence of a group of calciphyres containing a remarkable assemblage of rare carbonate-silicate minerals and feldspathoids, in a gabbro-limestone contact near Nanjangud, Mysore, India. This occurrence has been cited by Shand (1945, p. 506), as favouring Daly's hypothesis of the genesis of alkaline rocks. Many of the mineral assemblages described by Rama Rao, could have formed only under low pressure and very high temperature conditions of the Sanidinite facies, and their occurrence in a gabbro-limestone contact of Archaean age seemed exceptional. A brief field study of this occurrence was therefore made, and several specimens of calciphyres and related rocks collected. These, together with a suite of specimens from the area sent by Mr. B. Rama Rao to the Department of Mineralogy and Petrology, Cambridge University, kindly placed at the disposal of the writer by Professor C. E. Tilley, were carefully examined, and the results are presented below.[2]

Geological Setting

The calciphyres and granulites occur as intercalations in a highly metamorphosed and deformed series of rocks comprising amphibolites,

[1] Published by kind permission of the Director, Geological Survey of India.

[2] When these specimens were first received at Cambridge, it became clear that a redescription of the assemblages would be necessary. Revision is now long overdue, and I am grateful to Dr. Subramaniam, who has had the advantage of studying the rocks in the field, for undertaking the examination of the material at Cambridge, as well as his own collection during his visit overseas. With the mineralogical reinterpretation now presented, I am in accord.—C. E. Tilley, 10th June, 1955.

granulites, and quartzites. They outcrop along the flanks of three hills ·2354, ·2394, and ·2602, N.E. of Nanjangud in Mysore. According to Rama Rao (1943, p. 21), the field relations of the rocks of the area are :

> " The calciphyre now under description, forms a component of a narrow belt of a composite series of granulitic schists which cover an area of about 2 to 2½ square miles. The belt runs in an east-north-easterly direction from the place where the road and the railway cross the river Kabbani, towards ·2602, for a length of about 4 miles varying in width from 5 to 6 furlongs. It is composed for the most part of a series of dark hornblende granulites of varying texture, and perhaps of varied origin, with thin intercalations of calciphyres and granulitic quartzo-felspathic schists, the whole series being intricately folded and intruded by the granitic rocks of the region."

The above observations are generally correct and the following rock types were distinguished in the field, forming a series : garnetiferous hornblende granulite, epidote granulite, calc schist, calc granulite, marble, sheared and mylonitized calc-granulites and marbles, amphibolite, quartz garnet granulite, and quartzite. These rocks have undergone intense deformation and consequent shearing and crushing, and have been later permeated by the granitic intrusions of the region. The calciphyres, calc-granulites and marbles, which occur as intercalations in these granulites and amphibolites, appear to be remnants of thin beds of impure limestones, which have been sheared and recrystallized during regional metamorphism. They occur as narrow bands and bouldery runs, lenses, and nodules in the hornblende granulites and amphibolites. The calciphyre bands east of ·2602 show these relationships. Rama Rao (1943, pp. 21–23) has described the association of calciphyres and gabbros as below :

> " The calciphyres are underlain here and there by thin beds of highly epidotized quartzo-felspathic granultic schists. But at some spots they are in direct contact with a coarse, speckled, dark hornblende rock which, from its present mineral composition and texture, may be classified as a hornblende gabbro or eucrite. This has baked, fritted, and ferruginized the edges of the calciphyre runs, where it comes into contact with them and shows a dark, dense, aphinitic selvage edge, of not more than an inch or two in width. Such selvage edges are highly calcified and in their weathered and decomposed phases look like dense, greenish brown or greyish, calciferous cherty layers or calcflintas. . . .
>
> The basic hornblende granulite in direct contact with the calciphyres has baked, fritted, and thermally metamorphosed them,

and also shows in places other evidences of contact alteration indicating thereby that it is later intrusive into the original calciferous rocks, and has not given rise to them by its own hydrothermal alterations."

The writer could not locate any gabbro-limestone contacts conforming to the above description of Rama Rao. It was found, however, that many calciphyre bands, had sheared and crushed margins, with formation of very fine grained types studded with tiny porphyroclasts. It is thought that during deformation and folding of these rocks, there was differential movement of the plastic limy layers in relation to the adjacent rocks, resulting in the development of calciphyres and marbles showing structures and textures, indicating shearing, crushing, and flowage. The hornblende gabbro referred to by Rama Rao as a later intrusion, is developed in force on hill ·2354, and is a lineated coarse amphibolite.

Mineralogy

As several rare carbonate-silicates, and feldspathoids had been recorded in these rocks, nearly a hundred thin sections were examined and the optical properties of the minerals observed determined. Larnite, merwinite, spurrite, kaliophilite, nephelite, hauynite, gehlenite, melilite, and several other minerals described by Rao from these rocks, were not found in the specimens examined. These rocks were found to carry the following minerals : Plagioclase feldspars An_{10} to An_{75}, microcline, scapolite, epidote-clinozoisite, garnet, amphiboles, clinopyroxenes, micas, chlorite, calcite, sphene, quartz, ores.

Plagioclase feldspars.—Plagioclase feldspars occur as porphyroclasts and small plates in the marbles and calciphyres, and as large twinned plates or untwinned grains in the granulites and amphibolites. The compositions of these plagioclases from various rock types determined by immersion method, are as below :

Rock Type.	α[1]	*Composition.*
Marbles and Calciphyres .	1·552–1·554	An_{48-50}
Calc-schists . . .	1·554–1·556	An_{50-55}
Calc-granulite . . .	1·556–1·566	An_{55-75}
Epidote amphibolite . .	1·533–1·536	An_{10-15}
Amphibolites . . .	1·548–1·550	An_{40-45}

Microcline.—Porphyroclasts of microcline are seen in the calciphyres and marbles, and occasional plates of the mineral showing cross hatching are found in the granulites and amphibolites. In some of the porphyroclasts of microcline, the cross-hatching is incipient ; such grains have been perhaps mistaken for kaliophilite or leucite by Rao.

[1] All refractive index data given in this paper are ± ·003.

Scapolite.—Many of these rocks contain small amounts of scapolite, but in one specimen collected from a calciphyre-hornblende granulite contact, the mineral made up nearly half the rock. The mineral is easily recognized by its low refringence and high birefringence. Basal sections of the mineral showed perfect uniaxial figures with negative sign, and these have perhaps been mistaken for nepheline by Rao. The following values for the indices of refraction of these scapolites indicate them as mizzonites with 60–80 per cent meionite.

N_e 1·555–1·560
N_o 1·580–1·589

Epidote-clinozoisite.—Clinozoisite-epidotes occur in abundance in the calc-granulites and calciphyres, in the form of grains with incipient crystal form, acicular aggregates, tiny prisms and large idiomorphic plates. Granular aggregates and acicular crystals are found developing in a carbonate base, coalescing into sheaf-like aggregates, which in turn develop into large plates, replacing the earlier garnets, feldspars, and carbonates. They also show vermicular intergrowths with plagioclase and occasionally with quartz, simulating myrmekite. The clinozoisites are characterized by their low birefringence and consequent "ultra-blue" interference colours, and very low extinction angles ($\alpha \wedge c$ 0–5°). Rama Rao has perhaps mistaken some of the tiny prisms of clinozoisite for melilite. The epidotes form large plates, which are faintly pleochroic, with high birefringence. The indices of refraction of a few grains of these minerals from different rocks indicated the following values :

$\alpha = 1 \cdot 708–1 \cdot 722$
$\gamma = 1 \cdot 712–1 \cdot 740$

Some of the granulites carry grains of this mineral with γ higher than 1·740, indicating a higher tenor of epidote molecule.

Garnet.—Pale pink to colourless garnets are seen in the calciphyres and granulites, while the hornblende granulites carry pinkish garnets. In the sheared marbles they are almost colourless, occurring as pophyroclastic aggregates of shattered grains. The index of refraction of these garnets which ranges from 1·778–1·792, their colour, and their paragenitic relations indicate them to be composed of grossularite, andradite, and almandite molecules.

Amphiboles.—Three varieties of amphiboles have been noticed in these rocks, with the following optical characters :

1. Colourless or pale green amphibole in epidote-amphibolite with $\alpha = 1 \cdot 622$, $\beta = 1 \cdot 631$, $\gamma = 1 \cdot 641$; 2 V negative, large ; $\gamma \wedge c = 15 \pm 2°$; pleochroic in pale greens.

2. Olive green hornblende in granulites and marbles $\alpha = 1 \cdot 652–$

1·656, $\beta = 1·660–1·664$, $\gamma = 1·674–1·680$; $\gamma \wedge c$ 18 ± 2°; 2V negative, large; X = pale yellow, Y = pale olive-green, Z = olive-green X < Y < Z.

3. Brown hornblende in coarse amphibolites (Rao's hornblende gabbros) $\alpha = 1·656–1·659$, $\beta = 1·662–1·666$, $\gamma = 1·680–1·686$; $\gamma \wedge c = 19 \pm 2°$; 2 V negative, large; X = pale yellow, Y = brown, Z = deep brown; X < Y < Z.

The above optical properties show them to be calcic and sub-calcic hornblendes.

Clinopyroxenes.—Clinopyroxenes with the following optical properties are observed in some of the calicphyres, and amphibolites, which show them as belonging to the diopside-hedenbergite group :— $\alpha = 1·686–1·706$; $\beta = 1·700–1·710$, $\gamma = 1·710–1·722$; $\gamma \wedge c$ 41 ± 3°, faintly pleochroic in pale greens.

Micas.—Minor amounts of brown mica (phlogopite ?), muscovite, and sericite are seen in many of the calc-granulites, calciphyres, and amphibolites.

Chlorite.—Aggregates and small plates of chlorite are seen in the granulites and amphibolites displaying faint pleochroism in greens, and low birefringence.

Calcite.—Occurs as plates with lamellar twinning, and as granular aggregates in the marbles and calciphyres. Some of the sheared marbles show calcite with bent lamellae.

Sphene.—Sphene is present in abundance in the calciphyres and calc-granulites, and in small amounts in the amphibolites and hornblende granulites. The mineral occurs as grains, small plates, and typical lozenge or wedge shaped crystals readily recognized by their extreme refringence and birefringence.

Quartz.—Occurs as ovoid aggregates of grains with crenulate margins, displaying intense strain shadows, forming porphyroclasts in the sheared marbles. Small amounts of quartz with undulose extinction and sutured margins occur in the granulites and amphibolites

Ores.—Stray grains of ore are noticed in the hornblende granulites and amphibolites.

Petrology

The rocks examined may be classified into three main types as below:—

1. Calciphyres and calc-granulites containing variable amounts of lime garnet, plagioclase, diopside, green hornblende, epidote-clinozoisite, sphene, microcline, and quartz in a matrix of calcite.
2. Sheared and mylonitized calciphyres and marbles with porphyro-

clasts of plagioclase, microcline, quartz, garnet, and epidote-clinozoisite, in a carbonate base showing flowage and shearing.

3. Hornblende granulites, garnetiferous amphibolites, epidote amphibolites, and coarse amphibolite.

The first two types represent Rama Rao's calciphyres and variants, while his hornblende gabbro is the coarse amphibolite listed under type 3.

The calciphyres and granulites are medium to fine-grained rocks with a saccharoidal texture, characteristic of recrystallized marbles. Hand specimens are white, buff, or grey in colour, studded with the tiny porphyroclasts of resistant quartz, garnet, etc. Thin sections show these rocks to be largely composed of calcite, plagioclase An_{45-75}, pale pink garnet, clinopyroxene (diopside), olive green hornblende, and epidote-clinozoisite, with variable amounts of sphene, microcline, quartz, brown mica (phlogopite ?), scapolite, and ores. All the above minerals are set in a matrix of calcite occasionally showing bent lamellae. The epidote-clinozoisite group of minerals are profusely developed in these rocks, the clinozoisite being readily identified from its characteristic " ultra-blue " interference colours. The epidotes show faint pleochroism and high birefringence. These minerals display vermicular diablastic intergrowths with plagioclase and sometimes with quartz, which have been considered nepheline-zoisite intergrowths by Rama Rao (1943, pl. 2, fig. 2). The development of prismatic and acicular clinozoisite crystals in carbonate base has already been referred to. Diablastic intergrowths of epidote-clinozoisite with plagioclase and quartz are quite common in marbles and high-grade lime silicate rocks. The plagioclase feldspar present in these rocks is generally An_{45-55}, but in one specimen of calc-granulite, plagioclase An_{75} and An_{55} were found occurring together. They occur as simple twinned or untwinned plates. Microcline is occasionally seen in these rocks, displaying cross-hatching along the margins. Micas, chlorite, and ores occur in types rich in clinopyroxenes and amphiboles. Scapolite is present in small amounts in many of the rocks, and in one type is abundant. Sphene occurs in all these rocks as grains and wedge-shaped crystals. The following are the important mineral assemblages found in this type:—

Calcite-clinozoisite-epidote-plagioclase-sphene.

Calcite-lime garnet-clinopyroxene-clinozoisite-epidote-sphene.

Calcite-green hornblende-lime garnet-clinozoisite-epidote-sphene.

Calcite-scapolite-diopside.

Williams, Turner, and Gilbert (1954, p. 240) consider such assemblages as characteristic of marbles of high grade amphibolite facies,

formed during regional metamorphism of impure limestones. Rama Rao's specimens M .3/255, 256, 257, 260, 264, 265, and 266 represent the above type.

The rocks of type 2 are very fine-grained and darker in colour, occurring along the margins of the calciphyres of type 1. Weathered surfaces are studded with tiny prominences which are found in thin sections to be porphyroclasts of quartz, garnet, and feldspar. Thin sections of this type show a thoroughly granulated and sheared matrix of carbonate in which porphyroclasts of plagioclase, quartz, microcline, garnet, and occasionally epidote-clinozoisite are scattered. The porphyroclasts of quartz are generally ovoid in shape, consisting of an aggregate of grains having sutured margins and displaying intense strain shadows. The feldspar porphyroclasts are generally made up of a single plate of plagioclase or microcline, the latter showing incipient cross-hatching. The porphyroclasts of epidote-clinozoisite and garnet are composed of shattered grains of the minerals. Diablastic intergrowths with quartz and plagioclase and development of prisms of clinozoisite are noticed in porphyroclasts of epidote-clinozoisite. In some specimens, the matrix of carbonates and the porphyroclasts are completely mortarized or mylonitized, and in thin sections show textures suggestive of flowage due to plastic deformation. Occasionally the groundmass carbonates carry diffused iron-oxides, giving the rock a brown colour. Specimens M. 3/251, 252, 258, 261, 262, F. 309, 323, 351, and M. 1/843 in Rama Rao's collection represent this type.

The rocks of type 3 consist of hornblende granulites and amphibolites. The garnetiferous hornblende granulites and amphibolites are fine-grained, displaying a granoblastic texture in thin sections. They are composed of plagioclase An_{40-45} olive green hornblende, diopside, small prisms and plates of epidote-clinozoisite, garnet, and sphene with minor amounts of calcite, quartz, and scapolite. In another type a pale green amphibole is associated with plagioclase An_{10-15}, and epidote-clinozosite with minor amounts of sphene, diopside, and calcite. The mineral assemblage in the above types suggest them to be " sedimentary amphibolites " formed during regional metamorphism. A coarse variety of amphibolite containing brown hornblende, plagioclase An_{45}, diopside, and minor amounts of sphene, scapolite, and rarely epidote-clinozoisite is developed in force in the area around ·2354. It displays a linear structure due to the preferred orientation of the hornblende prisms. This type has been described by Rao as a hornblende gabbro (F. 321). The absence of epidote-clinozoisite and lime garnet, so abundant in the other amphibolites, and the presence of brown hornblende and abundant twinned plagioclase plates may perhaps reflect an igneous origin for these coarse amphibolites.

Conclusion

The foregoing descriptive account of the mineralogy and petrography of these rocks and their field relationship make it clear that the calciphyres and calc-granulites represent impure calcareous sediments which have undergone regional metamorphism. The present study has confirmed the doubts felt by the writer on the occurrence in an Archaean metamorphic terrain of rocks containing carbonate-silicate minerals like larnite, merwinite, and spurrite which are typical of high temperature low pressure limestone-gabbro contacts.

Acknowledgments

Professor C. E. Tilley, F.R.S., suggested re-examination of these rocks and placed at the disposal of the writer the Cambridge collection of Nanjangud rocks, received from Mr. B. Rama Rao. The writer is most grateful to him for according Laboratory facilities at the Department of Mineralogy and Petrology, Cambridge University, going through some of the thin sections of these rocks, and kindly reading this manuscript. The award of a Commonwealth Bursary by the Royal Society which enabled the writer to work at Cambridge is gratefully acknowledged. Dr. M. S. Krishnan, Director, Geological Survey of India, permitted the writer to make a field study of the Nanjangud area, and present this note, for which he is most grateful.

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Echinotiara arabica sp. nov., A Regular Echinoid from the Toarcian of Central Arabia

By R. V. Melville [1]

(PLATE XIX)

Abstract

The new species *Echinotiara arabica* is described and referred to the family Stomopneustidae Meissner, 1903. It is compared with other Liassic species of "*Stomechinus*" which are considered to be congeneric with it, and its relationships with the genera *Stomechinus*, *Psephechinus* and *Jeannetia* are discussed.

Introduction

THE new species described below is based on fifty-five specimens collected by Dr. W. J. Arkell in the Jebel Tuwaiq area of Central Arabia and presented by him to the Sedgwick Museum, Cambridge. The writer is indebted to him and to Mr. A. G. Brighton for the opportunity of studying this material.

Family STOMOPNEUSTIDAE Melssner, 1903

Genus Echinotiara Pomel, 1883

Echinotiara arabica sp. nov.

Stomechinus sp. Arkell, 1952, p. 249.

Syntypes.—Sedgwick Museum Nos. F. 10820–39, 11937, 12001–5, from the Lower Marrat Formation (Lower Toarcian, *Bouleiceras* Bed), Locality 55 (of Arkell, 1952), jebel 24·8 kilometres S. ·01° W. of Ain Bukhara, Jafair Trail, Jebel Tuwaiq, Central Arabia.

Diagnosis.—Corona of moderate height or somewhat depressed; pentagonal, rounded-pentagonal or subcircular in ambital outline; adapical surface slightly convex or slightly impressed; adoral surface slightly or moderately tumid with gentle invagination around the peristome; apical system (Text-fig. 5) dicyclic; ambulacra (Text-figs. 5, 6) composed of diademoid triad compound plates except in the adapical region, where simple, primary plates and dyad compounds occur; pore-pairs uniserial adapically, becoming triserial in the triad compound plates; interambulacral plates low, approximately equal in height to a compound ambulacral plate in the ambital region; primary tubercles imperforate, smooth, placed a little nearer the interradial than the adradial suture; secondary tubercles confined to the adradial tract, variable in number and disposition, though one nearly

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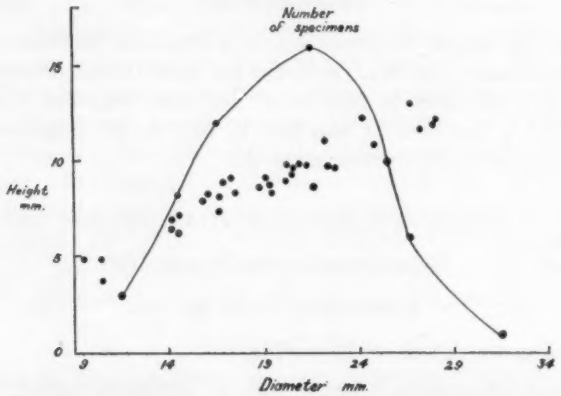
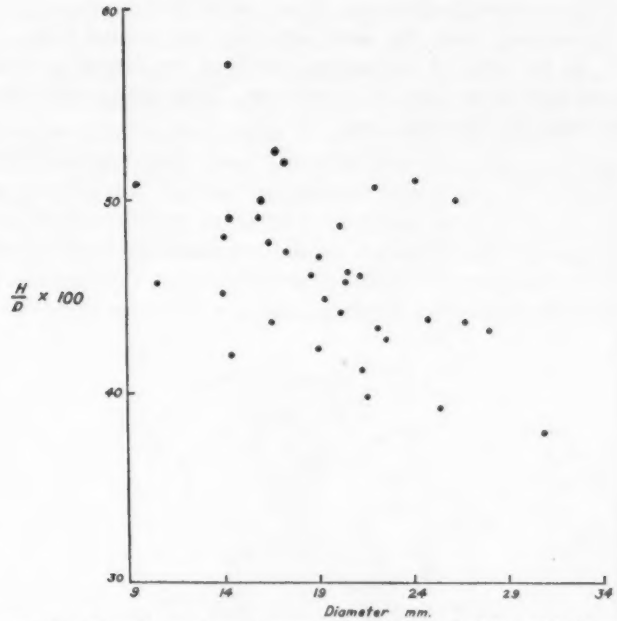
regular vertical series usually occurs ; a few small tubercles may also occur in the interradial tract below the ambitus ; there is a naked interradial space adapically ; periproct central, irregularly rounded, slightly elongated in the axis IV–1 ; peristome rounded-pentagonal, with feeble branchial slits and a slight embayment corresponding to each perradial suture, peristomial margin resorbed ; perignathic girdle (Text-fig. 7) weak, composed of low, straight, separated auricles and scarcely perceptible apophyses ; primary radioles short, smooth, with solid axis and very thin cortical layer.

Variation.—The material is excellently preserved and although some specimens are incomplete or crushed, thirty-eight were found to be

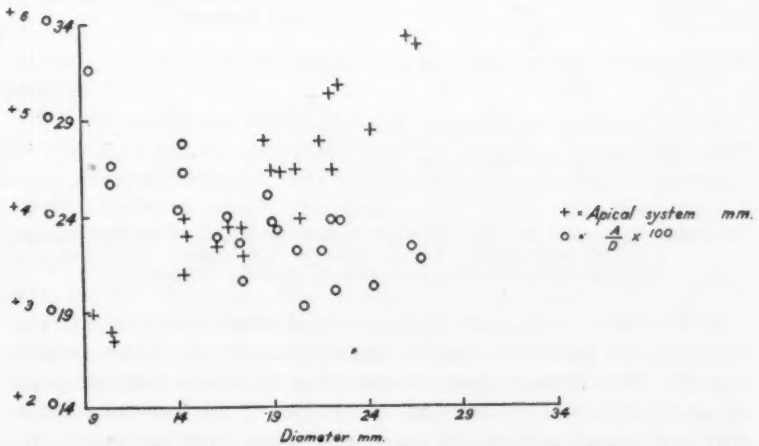


TEXT-FIG. 1.—Graph to show increase of height with diameter (dots) and variation in diameter against numbers of specimens (curve). The numbers denoting height in millimetres and numbers of specimens in a 5-mm. diameter range are the same.

adequately preserved to provide reliable measurements. This is not enough for a statistical analysis, but some idea can be obtained of changes with growth and of the pattern of variation (Text-figs. 1–4). The smallest specimen examined was 9·5 mm. in diameter and the largest just over 30 mm. Specimens between 22 and 28 mm. in diameter are common and are regarded as fully grown. The height is slightly less than half the diameter and decreases slightly with growth relative to the latter. Both the apical system and the peristome increase continuously in size with growth of the corona, but both decrease in size relative to the diameter, the former from 27 to 20 per cent and the latter from 45 to 35 per cent of that dimension in the sample examined. The width of every available ambulacrum and interambulacrum was measured at the ambitus and the arithmetic mean of each group of measurements (ambulacral and interambulacral)

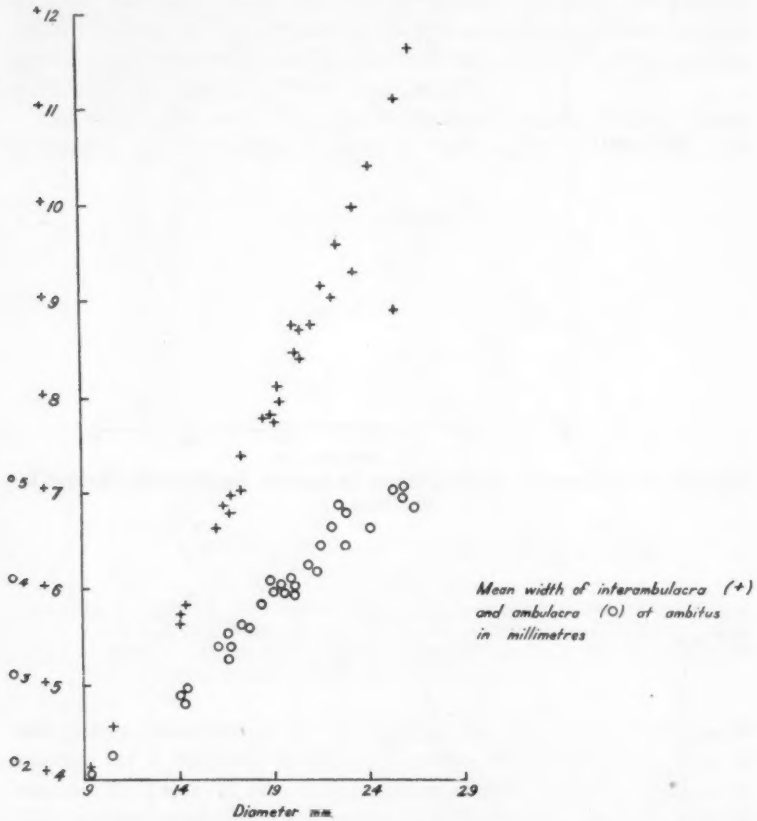


TEXT-FIG. 2.—Graph to show decrease in relative height with increase in diameter.



TEXT-FIG. 3.—Graph to show increase of diameter of apical system with increase in diameter (+) and progressive decrease in relative diameter of apical system (o).

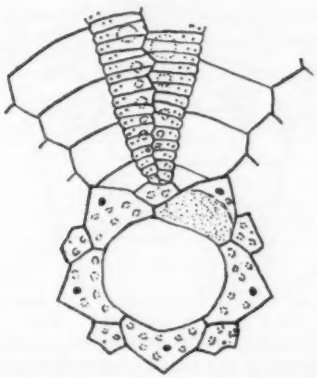
was used in comparing specimens. It was found that the interambulacra grow more rapidly than the ambulacra, for the ambital width of the latter is 53 per cent of the ambital width of the former in younger forms and only 44 per cent in larger forms. These changes with growth are illustrated in Text-figs. 1–4.



TEXT-FIG. 4.—Graph to show increase in ambital width of interambulacra (+) and ambulacra (o) with increase in diameter. Note that the interambulacra increase more rapidly than the ambulacra.

In the smaller forms, up to about 16 mm. diameter, the pore-pairs are uniserial from the apical system to the ambitus and very feebly arcuate adorally. Nevertheless, triad compound plates extend from the peristome to well above the ambitus, as is shown by the fact that there is only one primary ambulacral tubercle to every three pore-pairs. In fully grown specimens (Text-fig. 5) there are three or four primary plates next to the ocular plate ; these are followed by two or three dyad

compounds, each with a simple primary plate following adorally. The triad compounds which occupy the rest of each area are of diademoid type. Adapically the sutures between the three components run straight from adradial to perradial suture, but lower down these sutures are drawn together in the middle of the compound plate until on the adoral surface they nearly meet under the boss of the primary tubercle, almost dividing the median component into a poriferous, adradial part and an imperforate, perradial part. It will be noticed (Text-fig. 6) that the suture of the lowest component is more arched than that of the apicad component ; thus, if the median plate were reduced to a demiplate, the result would be a typical echinoid compound, consisting of



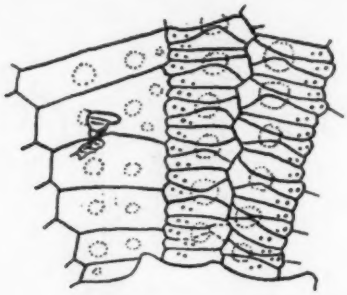
TEXT-FIG. 5.—Drawing to show structure of apical system and adapical ambulacral structure of a specimen 20·7 mm. in diameter. F. 10829. × 8 approx.

a larger orad and a smaller apicad primary plate embracing a median demiplate.

The interambulacral ornament is for the most part sharply divided into primary tubercles and miliary granules. The boss of each tubercle is circular or transversely oval (with straight orad and apicad margins) in plan and the parapet is smooth and well defined. The mamelon is spherical, glossy, and imperforate. The scrobicules are sharply defined by the closely packed granules which occupy the remainder of each plate, but there is no well-differentiated scrobicular circle. The scrobicules are contiguous adapically, down to the limit of the narrow, median naked space ; below this they are confluent so that the granules form a raised meridional band with scalloped edges. The naked median space may extend from the apical system almost to the ambitus or only half as far. Mamelonate secondary tubercles are variably developed in specimens of the same order of size and even in different interambulacra in the same specimen ; one or two may occur in the

adradial tract of each plate at and below the ambitus and they may extend sporadically, and not necessarily on every plate, over halfway to the apical system. Granules are present in the adradial tract only in the adapical region.

On the adoral surface the primary interambulacral tubercles approach nearer to the interradial suture in an adoral direction (Text-fig. 6). Deutler (1926) has observed the same phenomenon in *Echinus* and suggests that it is due to resorption of already formed material along the interradial suture, resulting in the diminution of the interradial tract of the plates in the adoral region.



TEXT-FIG. 6.—Drawing of adoral ambulacral and interambulacral structure of a specimen 26·4 mm. in diameter. Note the greater curvature of the apicad suture of the orad component of each compound ambulacral plate and the adoral convergence of the primary interambulacral tubercles towards the interradial suture. F. 10825. × 8 approx.

The ambulacral ornament is similar in style. The primary tubercles are equal in size to those of the interambulacral plates just below the ambitus but they diminish more rapidly adapically. Granules form a raised, meridional perradial band and are confined to this band except for a few, in large specimens, between the primary tubercle and the pore-pair. Three or four small secondary tubercles may occur perradially in the ambital region. The pores are nearly circular and each pair is tilted perradially ; there are no peripodia but successive pairs are separated, from just above the ambitus to the peristome, by a ridge situated between the pore-pair and the apicad suture.

The apical system is always dicyclic as far as can be seen, though ocular I may be just insert in some imperfect large specimens. All the plates bear granules similar to those of the coronal plates. The madreporite is generally tumid and well defined, but it may be inconspicuous. The periproct is irregularly rounded and slightly elongated in the axis IV–1. No trace of the periproctal plates has been seen.

The peristome is a rounded pentagon in outline. The branchial

slits are broad and shallow with a sharply defined rim and there is a weak embayment of the margin at each perradial suture. The perignathic girdle (Text-fig. 7) consists of short, straight auricles slightly inclined adradially, and very feeble apophyses with a small interradial knob. A single demipyramid has been seen. It shows the striated interface with the adjoining demipyramid but is too imperfect for full description. It was apparently short and squat with a smooth upper surface. The primary radioles are short and smooth with a solid axis and a very thin cortical layer (Plate XIX, fig. 5). There is no sign of the polycyclic condition illustrated by Mortensen (1935, text-fig. 295, p. 495) in *Stomopneustes*.

Affinities.—The type species of *Echinotiara* is *Echinodiadema bruni* Cotteau, 1869, from the Bathonian of Niort, France. From a subsequent figure and description (Cotteau, 1884, p. 671, pl. 444, figs. 1–6), this species differs from *E. arabica* in its more globular form, in its relatively smaller primary tubercles and less crowded granules and in the absence of a naked adapical space in the interambulacra. Cotteau

TEXT-FIG. 7.—Drawing of part of the perignathic girdle of an imperfect fully-grown specimen. F. 10821. × 10 approx.

figures a specimen 18 mm. in diameter with ambulacral structure similar to that of *E. arabica* of the same size. Mortensen (1935, p. 500) lists four other species, ranging from Bathonian to Maestrichtian, all of which differ from *E. arabica* in their more rounded outlines and less crowded granular ornament.

Stomechinus Desor, 1856, differs from *Echinotiara* in its generally larger size, in the greater development of secondary tubercles and in its more advanced ambulacral structure with reduced plates and with a primary tubercle only on each alternate compound ambulacral plate. In *Psephechinus* Pomel, 1883, there is also more development of secondary tubercles and more advanced ambulacral structure and in both these genera the branchial slits are deeper and stronger than in *Echinotiara*. Although typical species of these genera are easily placed, their limits are not well defined and revision of marginal forms is needed. *Stomechinus andinus* Philippi (1860, p. 146, pl. ii, figs. 11–13) differs from *Echinotiara arabica* only in its taller profile, posteriorly elongate periproct and uniserial pore-pairs (as figured), with oculars I, III, IV, and V insert. It has the general appearance of *Echinotiara* but the figures do not show whether there is a primary tubercle to each compound ambulacral plate or only to each alternate plate; this species may be a true *Stomechinus*. *S. liasicus* Tilmann (1917, pp. 696–8,

pl. xxvi, figs. 5*a–d*) is closely similar to *E. arabica*, differing only in its somewhat less crowded secondary ornament and in the fact that the pore-pairs are triserial throughout, even to the adapical extremities of the ambulacra. *Psephechinus steinmanni* Lambert (*in* Lambert and Thiéry, 1925, p. 571 = *S. andinus* Steinmann, 1881, p. 248, pl. xiv, figs. 4, 4*a–c*, *non* Philippi) is described as having a posteriorly elongate periproct, though this is not shown in the figure; all the oculars are insert and there is no naked median space in the adapical parts of the interambulacra. All these three species are from the "Lias" (precise age not stated) of South America and at least the last two are considered to be congeneric with *E. arabica*.

Jeannetia Mercier, 1936 (type-species *J. mortenseni* Mercier, by monotypy; see Mortensen, 1940, p. 357) is indistinguishable from *Echinotiara* on the basis of the published information and is here considered a junior subjective synonym of the latter.

Reference of the new species here described to *Echinotiara* is supported by the evidence of the Bathonian *E. somaliensis* Currie, 1927, for these two species are clearly closely related. No material of the type species nor of any of the Cretaceous species listed by Mortensen (loc. cit.) has, however, been available for examination and comparison with the former might lead to modification of the opinions here expressed on the affinities of *E. arabica* and the South American forms considered to be related to it.

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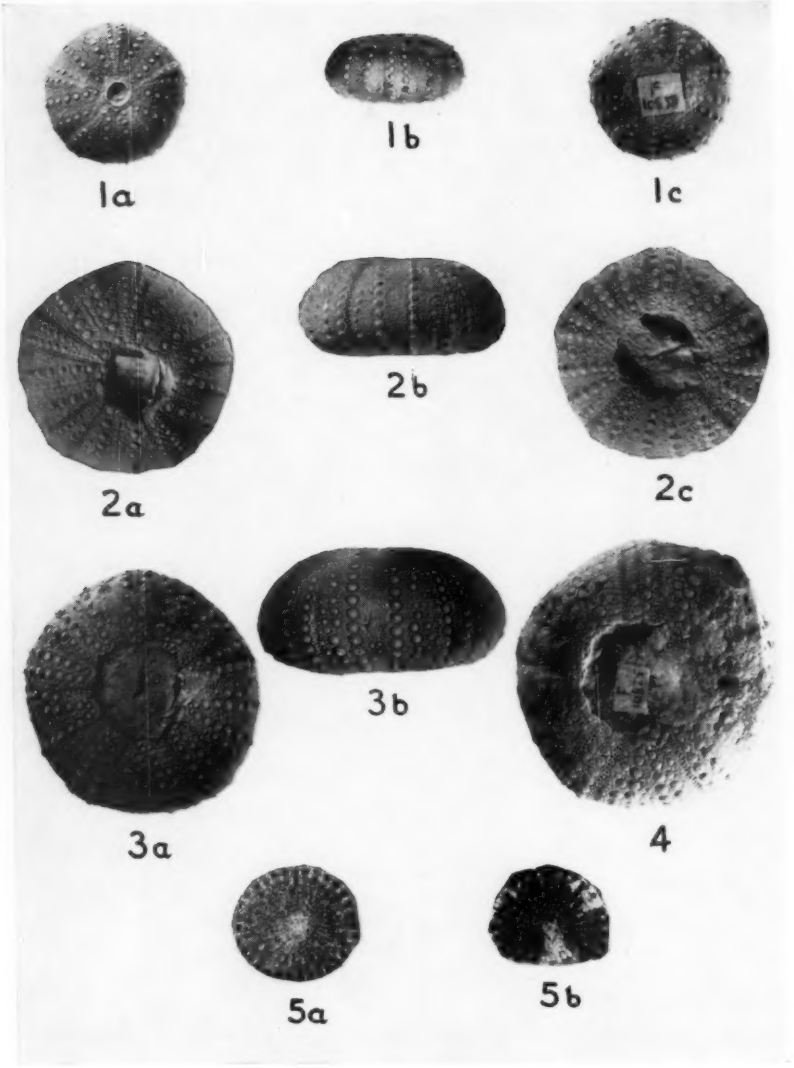
EXPLANATION OF PLATE XIX

Echinotiara arabica sp. nov.

FIG. 1*a–c*.—Adapical, ambital (ambulacral), and adoral views of a young specimen 14 mm. in diameter. F. 10838.



ECHINOTIARA ARABICA SP. NOV.

FIG. 2*a–c*.—Adapical, ambital (interambulacral), and adoral views of a specimen 20·8 mm. in diameter. F. 10831.

FIG. 3*a*, *b*.—Adoral and ambital views of a specimen 24·2 mm. in diameter. F. 12001.

FIG. 4.—Adoral view of a specimen 26·4 mm. in diameter. F. 10825. (See also Text-fig. 6.)

FIG. 5*a*, *b*.—Sections of a primary radiole. F. 11937*b*.

Fig. 5*a*, *b* × 30 approx.; all others slightly less than 1½ times natural size.

Some Notes on the Cardinal Process in the Productidae.

By Roland Goldring

Abstract

The cardinal process in the Productidae is divided into two main types, either bi- or trilobed. The process in several species, illustrating each type, is described and figured, and the development of both types compared.

Introduction

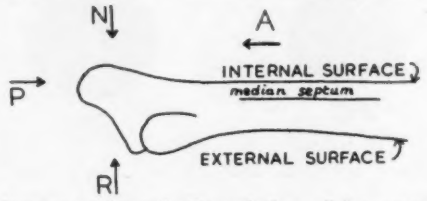
THE cardinal process is perhaps the least known part of the shell in the Productidae. This is not altogether surprising since it is rarely to be seen clearly, even when the specimen shows the remaining internal structures of the brachial valve. In most cases where it has been illustrated the figures are poor and small, with the notable exception of those by Kozlowski (1914). The process in some of the American Productidae has been described and illustrated by Sutton and Summerson (1943) who have shown that its variations have generic significance.

The Pilton Beds of North Devon yield several Upper Devonian and Lower Carboniferous species of the family and, as the preservation is as moulds, close examination can be made of the process, and other internal structures (with the aid of latex casts). A few other specimens from the Carboniferous Limestone of the Bristol area, similarly preserved, are also described, together with a silicified specimen from the Permian of the U.S.A.

The author is most grateful to Dr. Scott Simpson for criticism of the text and advice on the terminology, and also to Dr. H. M. Muir-Wood (British Museum, London) for discussion and information on the cardinal process of *Avonia youngiana* (Davidson).

Terminology

In order to compare the illustrations of the described cardinal processes, the several views of each are precisely defined. The posterior



Text-fig. 1.—Diagram to show the lateral view of the posterior median part of a brachial valve, with the internal and external surfaces perpendicular to the plane of the paper, and illustrating (i) the lateral view of the median septum and the cardinal process, and (ii) the direction of the other four views of the cardinal process, normal (N), reverse (R), anterior (A), and posterior (P).

median internal surface of the brachial valve is usually fairly flat and serves as a useful reference plane. In Text-fig. 1 it is shown horizontal and facing upwards. The plan of this surface is included in the *normal* view (N) of the process, and the oppositely directed view, showing the external surface of the valve, is called the *reverse* view (R). The three views perpendicular to these two are called the *posterior* view (P), *anterior* view (A), and *lateral* view (L), the direction of the *posterior* and *anterior* views lying in the median plane of the valve.

The orientations adopted for each view are more or less the same as were used by Sutton and Summerson (1943) and the ventral and dorsal views of these authors are synonymous with the *normal* and *reverse* views respectively.

Bilobed Cardinal Processes

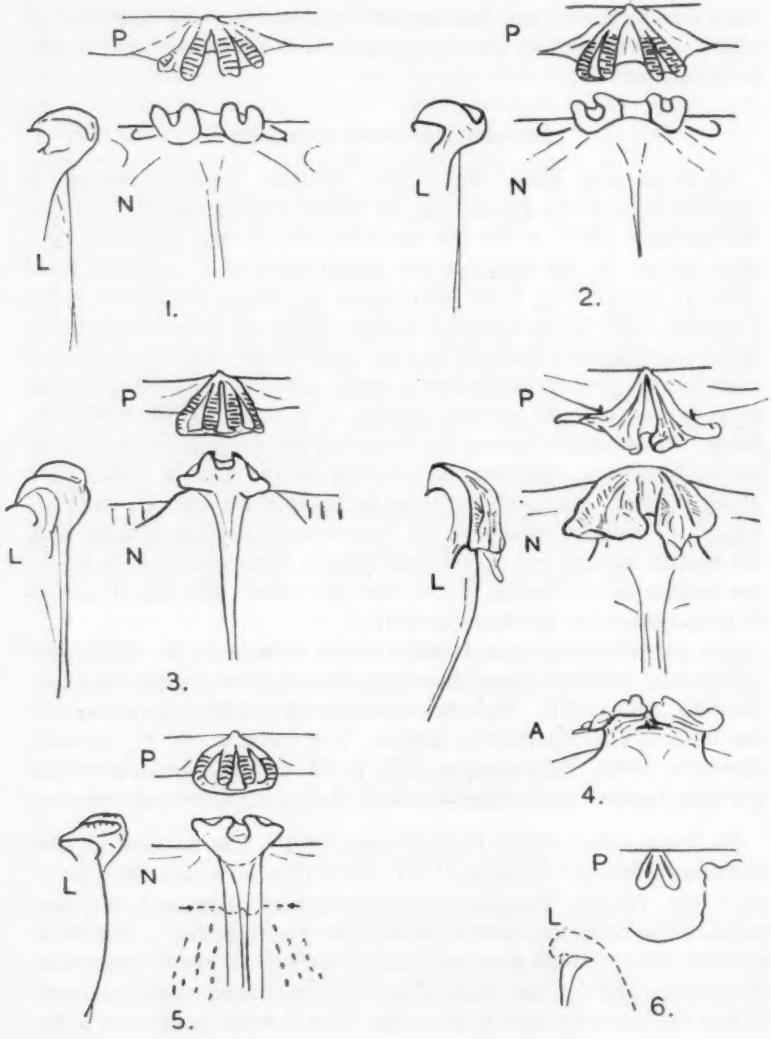
(*a*) *Productella* Hall, 1867. The bilobed cardinal process is typically developed in *Productella*. In species of the group of *P. goergesi* Paeckelmann (1931, p. 56) the two lobes are strongly separated by a deep sulcus. In the posterior and lateral views of *P. capillaris* Reed (1943, p. 78) (Text-fig. 2, BU 9081) and *P. piltonensis* Reed (1943, p. 75) (Text-fig. 2, BU 9082) each lobe diverges from a small knob close to the umbo and gradually increases in size. Although the lateral expansion is considerable, growth posteriorly is small. Each of the lobes is further strongly grooved, the grooves tending to expand slightly within the lobes. The posterior faces of the lobes, but not the grooves, have quite strong transverse striations, in contrast to the general smoothness of the process. Although the lobes merge laterally into the marginal ridges, the anterior margin of the process does not join directly with the median septum, but slightly overhangs a short smooth area before the median septum begins to rise from the valve. The dental sockets in both species are particularly deep.

The posterior and lateral views of the process of *P. subaculeata* (Murchison, 1840) (obtained by rubbing down), show a similar structure (Text-fig. 2, BU 9091). The sulcus dividing the two lobes is narrow and the lobes are comparatively higher. The process of *P. caperata* (Sowerby, 1840) (Paeckelmann, 1931, p. 62), is not so well known but it is close to those previously described, though comparatively smaller.

(*b*) *Productella*? *ultima* Paeckelmann, 1931. The cardinal process is distinctly bilobed (Text-fig. 2, BU 9083) (Paeckelmann, 1931, p. 70, pl. 3, figs. 16–18). The grooves in the lobes are deep, and the outer parts of the lobes are almost parallel to the hinge line. The main dividing sulcus, which does not curve anteriorly, is no stronger than the grooves, and the inner parts of the lobes tend to converge posteriorly so that the sulcus tends to form a tube. This is most clearly seen in the

normal view. The lateral view shows the strong posterior curvature of the process. Anteriorly it merges into the median septum and laterally the base, but not the lobes, merges into the marginal ridges. No dental sockets are present.

(*c*) *Productina fremingtonensis* (Reed, 1943). The cardinal process in this species is distinctly bilobed (Whidborne, 1896, p. 172) (Text-fig. 2, BU 9084, 9085). It projects considerably posteriorly and above the internal surface, and the median sulcus tends to become surrounded



by the convergence of the inner parts of the lobes. The grooves on each lobe are broad, and the posterior surfaces of the four parts of the lobes have strong transverse striations. Anteriorly the process merges into the median septum, which rises from within a broad groove. No dental sockets are present and marginal ridges are only poorly developed near the process.

(*d*) "*Linoproductus*" cf. *hemisphaericus* (Sowerby, 1823). The cardinal process in this species is essentially the same as in *Productella* (above) (Text-fig. 2, BU 9086). It is bilobed, and the two lobes originate from a simple knob. The lobes, however, expand anteriorly over the internal surface, and appear as large "petals", supported from the shell anteriorly by septa. The grooves in each lobe do not differ from those in *Productella*, and the outer surfaces of the lobes are strongly striated in contrast to the smooth dividing sulcus. As in *Productella*, the anterior margin of the process overhangs slightly the median septum. No marginal ridges or dental sockets are present.

(*e*) Bilobed cardinal processes not unlike those already described have previously been figured. Davidson's illustrations (1857, pl. 37, figs. 2–3) of the process of *Gigantoproductus giganteus* (Martin) show a posterior view similar to the earlier part of the process in "*L*". cf. *hemisphaericus*. The anterior petal-like extensions of the lobes are absent, but the large surface in his fig. 2 is similar to the base of the process in *hemisphaericus*, and the anterior expansion shown by Davidson is identical with the base of the septa supporting the lobes in *hemisphaericus*. The cardinal process of *G. giganteus* has been described as tetralobed, as have other species of *Gigantoproductus*. This is not

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TEXT-FIG. 2.—Camera lucida drawings.

1. *Productella piltonensis* Reed, 1943. Downend, Croyde Bay, Pilton Beds. Upper Devonian, *Wocklumeria* zone (VI). (BU 9082.) N, P, and L views. × 5.
2. *Productella capillaris* Reed, 1943. Sminhay, near Wiveliscombe, Pilton Beds. Upper Devonian, *Wocklumeria* zone (VI). (BU 9081.) N, P, and L views. × 5.
3. *Productella? ultima* Paeckelmann, 1931. Kuhlendahl, near Velbert, Germany, west of Inn and signal-box, Étroeungt Beds. Upper Devonian, *Wocklumeria* zone (VI). (BU 9083.) N, P, and L views. × 7.
4. "*Linoproductus*" cf. *hemisphaericus* (Sowerby, 1823). Wick, near Bristol, Wooton's Quarry. Carboniferous Limestone. Viséan S_1. (BU 9086.) N, A, P, and L views. × 3.
5. *Productina fremingtonensis* (Reed, 1943). Barnstaple, Fremington, S. end of beach, Pilton Beds. Lower Carboniferous, *Gattendorfia* zone (I). (BU 9084, 9085.) N, P, and L views. × 12.
6. *Productella subaculeata* (Murchison, 1840). Near Beaulieu, Boulonnais, Calcaire de Ferques. Upper Devonian, Frasnian. (BU 9091.) P and L views. × 5.

morphologically correct, and, so far as is known, no true tetralobed processes occur in the Productidae.

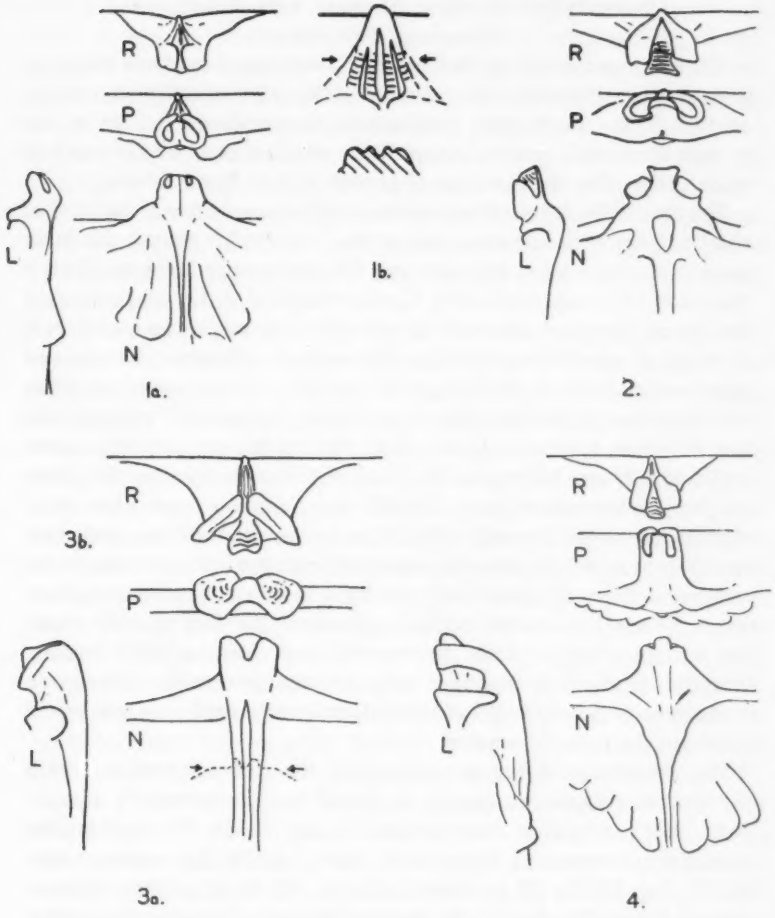
"Trilobed" Cardinal Processes

(*a*) "*Avonia*" *walcottiana* (Girty, 1908). The cardinal process in this species (King, 1930, p. 85) (Text-fig. 3, BU 9087) is quite different from those described above and the dividing sulcus is here replaced by what appears in the normal view to be an additional median lobe. In the reverse view the process originates near the umbo as a small knob, as in *Productella*, and, again as in *Productella*, it shortly divides into two with a narrow median sulcus. The two lobes are also grooved and transversely striated. However, the median sulcus does not expand posteriorly but fades and the inner parts of the two lobes converge and unite. The outer parts of the lobes expand posteriorly and towards each other, curving over and touching the median coalesced pair, and almost making contact with each other. What were grooves on the two lobes become almost enclosed tubes and the striated surfaces are mostly enclosed within the tubes. In the normal view the process is quite smooth and shows only a slight median sulcus. The process merges laterally into marginal ridges which diverge gradually from the margin, and anteriorly into the median septum.

(*b*) "*Avonia*" *praelonga* (Sowerby, 1840). The cardinal process in this species (Paeckelmann, 1931, p. 105) (Text-fig. 2, BU 9088, 9089) is very similar to that in "*A.*" *walcottiana*. The process is more strongly curved posteriorly and the tubes are not visible at all in the normal view. The cardinal process is not higher than the median portion of the internal surface, and the outer parts of the lobes do not converge so closely as in "*A.*" *walcottiana*. The process merges both laterally into strong marginal ridges, which do not diverge from the margin, and anteriorly into the median septum.

(*c*) *Buxtonia scabricula* (Martin, 1809). In the normal view, the cardinal process of this species (Davidson, 1857, p. 169) is distinctly bilobed (Text-fig. 3, BU 9090, 364) and projects considerably beyond the hinge line. In the reverse view the earlier part of the process is bilobed as in *A. praelonga* and *A. walcottiana* but the outer parts of the lobes do not noticeably expand, nor do the grooves in each widen till almost one-third the length of the process has been reached. The lobes are also strongly supported laterally by a thickening of the shell margin. The grooves do not markedly develop into tubes.

The process does not clearly merge into, although it adjoins, the marginal ridges, and merges essentially into the median septum, which in this genus is characteristically bifid posteriorly. The median groove does not continue into the median ventral sulcus of the process.



TEXT-FIG. 3.—Camera lucida drawings.

1. "*Avonia*" *walcottiana* Girty, 1908. Glass Mountains, Texas, U.S.A. Word Formation, Permian. (BU 9087), 1*a*. N, P, R, and L views × 5. 1*b*, part of the posterior view and section. × 11.

2. *Linoproductus cora* (D'Orbigny, 1842). After Kozlowski, 1914, p. 14. fig. 8. N, P, R, and L views. × 3.

3. *Buxtonia scabricula* (Martin, 1809). Wick Rocks, near Bristol. Carboniferous Limestone, D_3 zone. 3*a* (BU 9090), N view, and L view reconstructed with aid of 3*b*. × 5; 3*b* (BU 364), P and R views. × 5.

4. "*Avonia*" *praelonga* (Sowerby, 1840). Croyde Bay, and Sminhay, near Wiveliscombe, Pilton Beds. Upper Devonian, *Wocklumeria* zone (VI). (BU 9088, 9089.) N, P, R, and L views. × 3.

Comparisons between Bilobed and "Trilobed" Cardinal Processes

The observations on the bilobed and "trilobed" cardinal processes suggest that, basically, they do not differ so markedly as appears on first sight. Both types originate as simple knobs (so far as can be seen from their external appearance) which shortly divide into two lobes. Thereafter the direction of growth in both types differs.

The first of the three most important differences between the bilobed and "trilobed" processes is that in the "trilobed" process the inner parts of the two lobes coalesce and the appearance of three lobes is presented. This was realized by Kozlowski (1914, p. 12) who suggested that it was more convenient to describe this type of process as trilobed, although it was not morphologically correct. However, Sutton and Summerson (1943, p. 329), who did not refer to Kozlowski, consider that there are essentially three lobes in the "trilobed" process, and it is therefore basically distinct from the bilobed process. Licharew (1935, p. 288) and Miloradovich (1945, p. 499) also consider that there are three independent lobes. Sutton and Summerson attached most importance to the normal rather than to the reverse view, and their descriptions of the process are developed from the internal towards the external surface, the latter only receiving brief and inadequate attention. Since the internal surface represents the last growth stage, this surface may be liable to variable deposition of shell matter. Morphologically it is therefore more reasonable that the description of the process should begin at the earliest formed part, i.e. close to the umbo on the external surface.

The differences in the appearance of the internal surface within one type of process are evident in Sutton and Summerson's illustrations. For example, in *Juresinia* (pl. 53, figs. 22, 26, 29) considerable variation is present in the normal views, whilst the reverse views (pl. 53, figs. 23, 27, 30) are more uniform. Similarly, in their illustrations of *Echinochonchus* (pl. 54, figs. 11, 14) the two normal views differ considerably and one hesitates to accept Sutton and Summerson's conclusion that the process of *Echinochonchus* "*is distinctly bilobed*" on the internal surface, since in fig. 14 it is not bilobed. Sutton and Summerson described the reverse view of *Echinochonchus* (1943, p. 327, pl. 54, fig. 12, 13) as "*side lobes join at an angle below the center lobe*". This view might also be described thus: the cardinal process begins as a small knob close to the umbo, which shortly divides into two lobes, separated by a strong median sulcus. From this form of development it would then be quite clear that the process is basically bilobed and not trilobed. The cardinal processes of both *Juresania* and *Echinochonchus* appear to be essentially similar to the process of "*A.*" *walcottiana.*

The early development of the process in the reverse view is not clear in any of Kozlowski's text-figures and no photographs of this view are included in his plates. His realization that the cardinal process is morphologically bilobed rather than trilobed did not apparently result from deductions based on the early growth stages of the process but on the ω-shape and pair of tubes. It is not known whether his specimens were sufficiently well preserved to show these early stages but, since all the present material as well as the North American material figured by Sutton and Summerson shows the initial bilobed character of the process there is no reason to suppose that Kozlowski's material was basically different.

The second difference is that in the " trilobed " process the grooves in each lobe often tend to become tubes, as the outer parts of the lobes converge together. Only a slight tendency towards this occurs in *Productella*. Sutton and Summerson give no indication that hollow tubes might be present in the processes they described, but these were clearly shown by Kozlowski (1914). His illustrations, which include normal, reverse, posterior, and lateral views, show various degrees of completeness in the development of the tubes. The strong striations on the inner surfaces of the tubes were considered by him (1914, p. 13) to represent interruptions in growth, but they may well be similar to the striations which are typically developed on the muscle impressions in both valves. If this is so then the muscles in some of the " trilobed " processes were largely attached within the tubes.

In the described specimens of *Productella* it is always the outer posterior parts of the lobes that are striated, and the grooves and median sulcus are smooth. However, Miloradovich (1945, p. 499, figs. 11–15) has recognized four types of process, based on the positions of attachment of the diductor muscles, and in the first, *Productella*, type he states that it is the grooves that are striated and the muscles are attached within them. This is also the case in his second type, characterized by *Marginifera*. In his other two types, *Linoproductus* and *Striatifera*, the grooves are smooth and the muscles are attached to the lobes. If Miloradovich is correct then two different types of process are present in *Productella*, the one where the muscles are attached in the grooves and the other where the muscles are attached to the outer, posterior parts of the lobes.

Thirdly, the " trilobed " process projects much further posteriorly from the hinge line. This difference is not so general as appears from the processes described here. In several species of *Productella* the process, typically bilobed, does project considerably posteriorly, as in *P. hallena* Walcott (Sutton and Summerson, 1943, pl. 53, figs. 3–5).

The direction which the striated surfaces face is also markedly different in the two types. Whereas in the bilobed process they may be

seen in the posterior and normal views, in the " trilobed " process they can only be seen in posterior and reverse views. Although the orientations of these striated surfaces differs in the two types, in respect to the rest of the brachial valve, their relationship with the pedicle valve is more or less the same. The visceral cavity in the described species with " trilobed " processes is large and the brachial valve is flat, whereas in the described species with bilobed processes the visceral cavity is comparatively thin and the brachial valve follows quite closely the curvature of the pedicle valve. In species where the visceral cavity is large and the brachial valve flat the angle of rotation of the brachial valve about the hinge line during growth is greater than the angle of rotation when the visceral cavity is narrow. This explains why the growth of the process in species which have large visceral cavities is essentially posteriorly whereas in species with small visceral cavities the growth is interiorly perpendicular to this direction. In "*L.*" cf. *hemisphaericus* the process is supported anteriorly by septa which do not occur in any of the described species with " trilobed " processes. Additional support for the " trilobed " process is given by the coalescing of the inner parts of the two initial lobes and by the thickening of the margin at the process, as in *Buxtonia scabricula.*

Linoproductus Chao, 1927

Since Chao erected *Linoproductus* in 1927 there has been some confusion between it and *Striatifera* Chao, 1927, *Gigantoproductus* Prentice, 1950 (= *Gigantella* Sarytcheva, 1928), and *Kansuella* Chao, 1928, and it is not easy to assign some species definitely to any one of these genera. Prentice (1949, p. 247 ; 1950, p. 436) has now more closely defined *Gigantoproductus* and, in particular, he has separated out the *hemisphaericus*-like Gigantoproductids from *Linoproductus hemisphaericus* (Sowerby). This species was, however, carefully excluded from *Linoproductus* by Chao (1927, 1928), mainly on account of the shape of the brachial valve. That part of Chao's definition of *Linoproductus* defining the shape of the brachial valve has not been retained by any subsequent authors in their definition of the genus, and Muir-Wood (1930, p. 105) included *hemisphaericus* in *Linoproductus.* The generic significance of the shape of the brachial valve will not be considered here, although it is undoubtedly great, and it is only intended to point out the difference that exists between the cardinal process of the type species, *L. cora* (D'Orbigny, 1842), and other species which have been assigned to *Linoproductus.* The process of *L. cora,* which has been figured by Kozlowski (1914, p. 14, fig. 8), and is reproduced here (Text-fig. 3), does not appear to be basically different from the " trilobed " cardinal processes already described. However, the initial bilobed part of the process is not visible and it seems to be

reduced, or perhaps almost completely suppressed. (This has also apparently taken place in *Dictyoclostus*.) On the posterior median internal surface there is a large hollow immediately anterior to the process. This process is quite distinct from the bilobed process already described (Text-fig. 2) in "*L.*" cf. *hemisphaericus*. Also *L. cora* has strong marginal ridges which are absent in cf. *hemisphaericus*. The cardinal process in the species from the Pilton Beds, *L.* cf. *corrugatus*, is also quite distinct from cf. *hemisphaericus* and, although the process of this species is not completely known there is a hollow, anterior to the process similar to that present in *L. cora*. This hollow is not evident in *Linoproductus* spp., figured by Sutton and Summerson (1943, pl. 53, figs. 16–21). The species from N. America and from the Pilton Beds have strong marginal ridges.

The difference between the processes of *L. cora* and "*L.*" cf. *hemisphaericus* has more than specific significance and cf. *hemisphaericus* cannot be retained within *Linoproductus*.

Avonia Thomas, 1914

The type species of *Avonia*, *A. youngianus* (Davidson) has a small bilobed cardinal process (personal communication from Dr. H. M. Muir-Wood). However, the process of the two species of Avonia described here are quite different and the process of *A. praelonga* is typical of the coalesced bilobed type with the development of tubes. The median septum merges directly into the process without any intervening hollow, and it is not bifid. Reed (1943, p. 97) erected a new subgenus, *Mesoplica*, with *praelonga* as the type species. This subgenus is not considered to be sufficiently well defined and *praelonga* is therefore retained in *Avonia*, following earlier authors. Paul (1937, p. 81) showed that *nigra* (Gosselet), once one of the most characteristic species of *Avonia*, had a bifid median septum, and Paul therefore appropriately assigned it to *Buxtonia*. The process is, however, unknown. Licharew (1938, p. 289) commented that a bifid median septum was probably not restricted to *Buxtonia* and, as an example, he cited *boulei* Kozlowski (1914, p. 47), which he assigned to *Avonia*. From an examination of Kozlowski's description and figures it seems that the species should be assigned to *Buxtonia* on external ornamentation. The common British Lower Tournaisian species *nigra* var. *bassa* (Vaughan) (Paeckelmann, 1931, p. 100) which is always assigned to *Avonia*, appears to have a small bilobed process (from examination of serial sections), and although the character of the median septum is not known the cardinal process of the variety is closer to species of *Productella* than to *A. praelonga*. These species assigned to *Avonia* on their closely similar external ornament, have strongly differing internal (and more fundamental) structures. On their internal structures

they may more closely be compared with *Productella* and *Buxtonia* than between themselves.

Conclusions

The differences between the two main types of cardinal process in the Productidae have been discussed and their development demonstrated. The posterior and reverse views are the most important aspects of the process, since only these give any real indication of its growth. The normal view, in contrast, is important only in so far as it indicates the relationship between the process and the adjoining internal structures, the median septum, and the marginal ridges.

Considerable variation of the cardinal process exists between species which have been assigned to both *Avonia* and *Linoproductus*. The variation is considered to be of more than specific significance and it is suggested that both these genera are polyphyletic.

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Glacial Melt-Water Spillways near Kidsgrove, Staffordshire

By E. M. YATES

ABSTRACT

As a result of the drainage contest between the Weaver headstreams and the headstreams of the Trent the west facing edge of the Potteries coalfield has been breached in a number of places, in particular at Kidsgrove. During the last retreat of the ice the Kidsgrove breach came ultimately to act as a spillway for the large lake contained between the ice and the coalfield. Before the breach was uncovered, however, a number of spillways were cut further east.

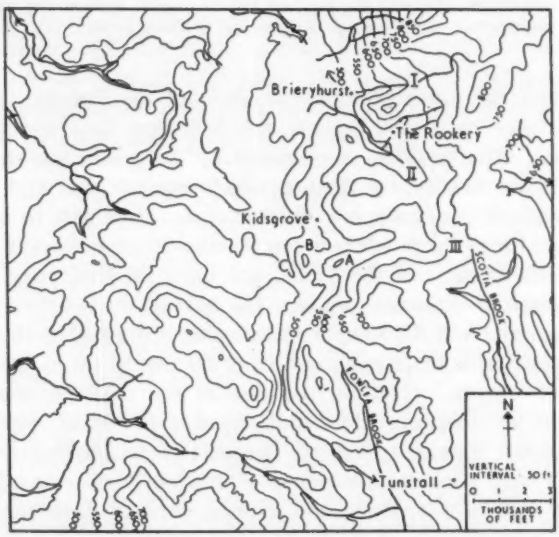
ALONG the north-western boundary of the Potteries coalfield, Keuper rocks rest against the Millstone Grit and the Coal Measures.[1] The junction is obscured by drift, and the strong but discontinuous west-facing feature which bounds the high ground of the coalfield is often a mile further east. Over part of its length this feature forms the divide between the west-flowing Weaver drainage and the headstreams of the Trent, and must for long have been an area of vigorous drainage-contest. The part of the coalfield between the high ground and the Keuper rocks which is drained by the Weaver headstreams forms an extension of the drift-covered lands of Cheshire. The Trent streams, which in the east of the coalfield show some adjustment to structure,[2] flow south-south-east, whilst most of the streams of the Weaver system commence their much shorter courses to the sea with a direction which is a little north of west. There is, therefore, little of a head to head struggle between these contestants, and certain of the gaps in the feature and its continuation southward (the discontinuities as above) appear to have resulted from an oblique beheading of Trent drainage by the more vigorous Weaver headstreams. The three major examples are situated at Kidsgrove, Audley, and Madeley, of heights 475 feet +, 500 feet +, and 375 feet +, respectively. They must all have provided through routes to the coalfield for the ice coming from Cheshire, before the coalfield as a whole was overridden. The valleys of the Trent streams which head back towards these gaps, the Fowlea Brook, the Lyme Brook, and the Meece Brook (in other words the valleys of the streams which suffered the piracies) are flanked with boulder clay.

When the ice began to retreat, these gaps no doubt allowed the escape of ice melt water ponded between the ice and the west facing

[1] Against the Carboniferous Limestone at Astbury. Grid reference 33/861593.

[2] E.g. the Fowlea Brook follows the Etruria Marl outcrop for four to five miles.

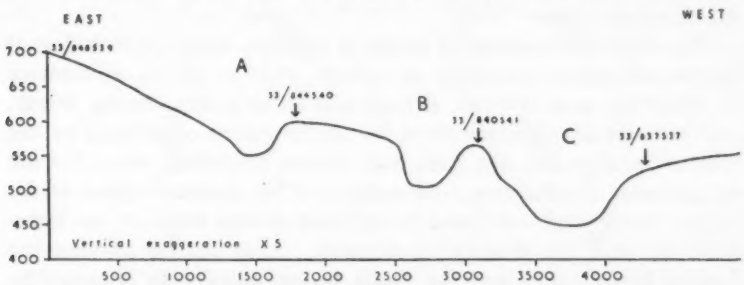
edge of the coalfield. Glacial sands occur at all three, and the alluvium of the valleys is at lower level than the flanking boulder clay. Jowett and Charlesworth, in their study of the glacial geology of the western flank of the Pennines, found evidence for a large number of periglacial lakes with associated drainage channels. Amongst these drainage channels were both the Madeley and Kidsgrove gaps. W. Gibson and C. B. Webb had likewise drawn attention to the gaps, including that at Audley, in their memoir. This paper concerns the northernmost of these three gaps—at Kidsgrove.



TEXT-FIG. 1.—Relief in the vicinity of Kidsgrove (from 1 : 25,000, Sheet 33/85). The drainage in the immediate environs of Kidsgrove has been disrupted by mining and is not drawn. This applies to the middle parts of the Brieryhurst and the Rookery streams, and to the whole of the upper course of the Kidsgrove stream.

From Kidsgrove north to Mow Cop there are three westward-opening valleys of the Weaver system. The most southerly of the three is mainly occupied by Kidsgrove and the adjacent colliery ; the hamlet of The Rookery is situated in the central valley ; Brieryhurst Farm in the most northern (Text-fig. 1). South and east of Kidsgrove are two headstreams of the Trent system—Fowlea Brook and Scotia Brook. The interfluves between the valleys of the Weaver headstreams do not, however, rise eastwards regularly to a culminating height on the main drainage divide. They are, instead, deeply notched. Thus the Brieryhurst–Rookery interfluve rises to 715 feet after a small undulation at 650 feet + (which is missed by the form lines). It then

falls to 650 feet + in col I, and finally rises to above 800 feet on the main interfluve. Similarly the Rookery–Kidsgrove interfluve rises to 654 feet, falls east to 600 feet + in col II and finally reaches 700 feet. Because of the oblique relationship of the Trent drainage to the Weaver drainage, the south side of the Kidsgrove valley is the interfluve from which Scotia Brook and Fowlea Brook flow south-south-east. That is to say the interfluve bounding the valley on its south side is not a secondary divide between minor headstreams of the Weaver, but the main English drainage divide, here curving westward. Like the minor interfluves it too is deeply notched. From the head of the Kidsgrove valley where it reaches 743 feet, it falls south-westward to col III, at about 650 feet, which leads through to Scotia Brook. Beyond this col it rises to 700 feet again, and then falls away westward. The decline westward is interrupted by three further channels



TEXT-FIG. 2.—Section through glacial spillways in the vicinity of Kidsgrove. Measurements are in feet. Grid references are given above the section.

A, B, C (Text-figs. 1 and 2). The third of these channels leads by way of a flat trough through to the Fowlea Brook valley and is the main Kidsgrove gap, as noted by Jowett and Charlesworth. In the trough the divide between the Trent and the Weaver drainage falls to beneath 500 feet, and is some 1,000 yards south of the general line of the interfluve.

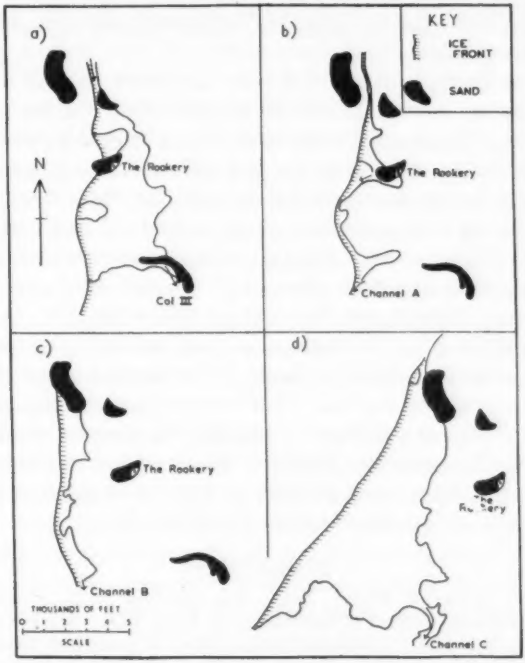
It is evident from Text-figs. 1 and 2, however, that there is a marked difference between the channels A, B, C and the cols in the interfluves. The latter are gentle features. The Brieryhurst, Rookery, and Kidsgrove streams are sub-parallel rather than parallel, so that headward erosion, plus any lateral activity by their small tributaries, might well give their interfluves an undulatory character. Furthermore, these streams were probably responsible for the dismembering of the upper Scotia Brook. Their interfluves may have been featured *ab initio* with remnants of the old valley. (It is to be noted that cols I, II, III are very approximately collinear with the Scotia Brook.) Irrespective of later events it might be suggested that A and B were similarly

the results of further piracies of tributaries of the Fowlea Brook by the Kidsgrove stream, after the capture which gave rise to C (the main throughway). This is most improbable, for such a series of captures by headward erosion must start at C and follow B, A. That is to say B would be functioning as part of a headstream of the Fowlea Brook after C had been produced, and A after B had been produced. It is to be anticipated that the levels of these features would then fall from C to A. The reverse is true. It is suggested therefore that B, A are overflow channels or spillways from Lake Kidsgrove, used before the retreat of the ice exposed the old windgap at C. A and B were cut by a body of water moving southwards along the ice face at different stages in the ice retreat. As will be seen they were probably cut where the interfluve was already dimpled by Fowlea Brook headstreams, but their sharpness of form is to be attributed to the action of fast moving melt water.

The suggested sequence of events in the later stages of evolution of the present relief is, therefore, as follows. Prior to the last ice advance to affect the area, Fowlea Brook, and its tributary, Scotia Brook, had been partially dismembered by acts of piracy committed by the Weaver headstreams, the gaps thus formed providing routes for the ice advance. Furthermore, the captures of the headward parts of the Scotia Brook may well have contributed to the form of the interfluves between the Weaver headstreams. After the ice advance the Fowlea Brook valley and the Scotia Brook valley were occupied by ice; both valleys bear the impress of ice in their smooth form. The boulder clay then deposited has been subsequently dissected. The extent of the dissection so far upstream, leaving only scrolls of boulder clay along the valley sides, suggests melt water rather than the activities of the normal drainage. For example, the long narrow sand spread which leads over col III into Scotia Brook was probably formed by a sub-glacial or periglacial stream, associated with ice resting in various positions near the col during the retreat.[1] The col has not the sharpness of incision shown by channels A, B, C, but a distinct valley-in-valley form is present. This stream, draining south, would have removed rapidly any boulder clay formerly present in the Scotia Brook valley. Further retreat westward exposed the rim of higher ground around the Brieryhurst, Rookery, and Kidsgrove valleys, and in the upper part of the valleys, between the ice front and that rim, the proto Lake Kidsgrove appeared. Since there is a spread of sand

[1] It has proved difficult to confirm the original mapping of this sand. Sand is in evidence in part, but elsewhere augering has revealed a stiff clay—probably derived from Coal Measure shales. A poor exposure beside the railway cutting 33/862530 showed clay overlying sand. Sub-glacial is therefore more likely than periglacial. It is fair to note that the ground has been disturbed by mining.

on the western flanks of Mow Cop, ranging from 600–675 feet (the north-eastern sands (Text-fig. 3*a*)), it would appear that a stream coming from the north along the ice front drained into the lake. The lake was in fact part of a southward drainage sequence between the ice front and the higher ground to the west.



TEXT-FIG. 3.—Series of maps illustrating the development of Lake Kidsgrove and the formation of the spillways.

(*a*) Drainage via col III to the Scotia Brook.

(*b*) Drainage via channel A to the Fowlea Brook.

(*c*) Drainage via channel B to the Fowlea Brook.

(*d*) Drainage via Channel C (the " Kidsgrove gap ") to the Fowlea Brook.

The continued western retreat of the ice exposed in turn, on the southern side of the Kidsgrove valley, the routes controlled by outlets A, B, C. The precise position of the outlets A and B was probably determined by stadial positions of the ice, and by pre-existing dimples in the interfluve due to the Fowlea Brook tributaries. It will be noted that both A and B have a valley-in-valley form (Text-fig. 2), and a reconstruction of the older valley from the upper slopes suggests that, at A, the melt water carved a channel 15 feet deep. This channel allowed the passage of water to Fowlea Brook direct.

The floor of the channel is at 550 feet. The water level of the lake was therefore considerably lowered. Indeed the older water body must have been virtually drained, the interfluves becoming clear of ice and water (Text-fig. 3*b*). There would have been a tendency for each tributary valley to become for a period a small separate body, together forming a chain of tiny lakes interconnected by the various cols in the interfluves, until the ice retreated sufficiently far west for drainage around the ridges.

The next stadial position of the ice was above channel B. At B the valley-in-valley form suggests that a pre-existing shallow col lowered the ridge to 550 feet—that is the level of A. Channel B therefore superseded channel A, and was in use as a spillway for a longer period for the channel has been cut 40 feet beneath the older floor. The lake continued to be little more than a narrow body of melt water escaping southward (Text-fig. 3*c*). Further retreat gave access to the Fowlea Brook valley via the main channel C, the old wind gap. This had already been altered by ice flow and cut below 500 feet. It functioned as an outlet for a considerable time since further retreat west would reveal no lower exits until the flanks of the western salient of the coalfield were completely ice free. That is to say this channel continued in operation until Lake Kidsgrove reached the dimensions sketched by Jowett and Charlesworth. Traces of the shore line of this stage are to be seen in the sharp break of slope at 475 feet at the foot of the west facing feature originally described (Text-fig. 3*d*).

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Survey of Two Drowned River Valleys in Devon

By P. B. McFarlane

Abstract

Seismic refraction surveys of the rock channels of the River Erme (S. Devon) and the Rivers Tawe and Torridge (N. Devon) suggest that at the time these were eroded the sea-level relative to land stood some 150 ft. lower than at present. Echo-sounding and sea-bed sampling off S. Devon have failed to reveal any trace of ancient channels in the sea floor at distances greater than one mile from shore.

Introduction

IT has been known for many years that the sea-level relative to land in S.W. England now stands higher than it once did. The studies by Worth (1890) of the estuaries of Plymouth and by Codrington (1898) in the River Dart, point to a relative rise of sea-level of about 100 feet in these estuaries since the buried rock channels were eroded. The reason for this relative movement of sea-level is not known but there has always been more than a suspicion that the drowned valleys were eroded in Pleistocene times. It is the purpose of this paper to show that at that time the sea-level in Devon stood some 150 feet lower than at present.

Seismic surveys of two river estuaries, that of the R. Erme in S. Devon and that of the Rivers Taw and Torridge in N. Devon, were made to measure the thickness of recent sediment in the estuaries and to locate the ancient rock channels. Since the S.W. Peninsula was unaffected by Pleistocene ice, it is safe to say that the thickness of recent sediment is related to a lowering of sea-level, and that the buried channels were not eroded by ice. In support of the seismic work, a programme of echo-sounding and sampling of the sea bed off S. Devon was carried out.

Technique

The seismic method used was essentially the same as that used on land, and for this reason estuaries had to be selected which have comparatively dry and hard surfaces exposed at Low Tide. The theory of the seismic refraction method is described by Bullard *et al.* (1940) and by Heiland (1946, p. 257).

The work in the Erme estuary was carried on in the main from the west bank and because of the variable surface conditions the equipment was transported on a hand-trolley hauled by four men. In cases where it was necessary to cross the river the equipment was manhandled.

The whole estuary was surveyed with a dumpy level from an Ordnance Survey bench mark at Mothecombe School. The present mean gradient of the river over the $1\frac{1}{2}$ miles from the Low Water Mark of Ordinary Tides is 5 feet/mile. The positions of the seismic lines were fixed

by chain and theodolite relative to suitable objects on shore. As a rule the geophone spacing was 60 feet so that the spread of six instruments was 300 feet long. In this survey, the spread was kept fixed to save time and shots were fired at various distances on both sides of the spread. In Text-fig. 1 the numbers referring to the various seismic lines have been placed near the centres of the corresponding spreads. A motor van parked on shore was used as a dark room, and in the early stages of the work when time permitted, the records were developed on the spot so that shots which had produced unsatisfactory records could be repeated.

In the Taw–Torridge estuary, the hard-packed surfaces of Saunton Sands and of the beach at Westward Ho ! allowed free use to be made of a Land Rover and enclosed trailer, the trailer being adapted as a dark-room and housing the recording equipment. On the South Gut (Line 8, Text-fig. 4) on Newquay Ridge (Line 5) and on the Penhill sandbank (Line 6) the experiments were conducted from an amphibious vehicle (DUKW). In this way, work could continue until the last possible moment before the tide flooded the line. The extra time made available by this arrangement was used in moving the spread three or four times so that a complete analysis of the structure under the line could be made after only one visit.

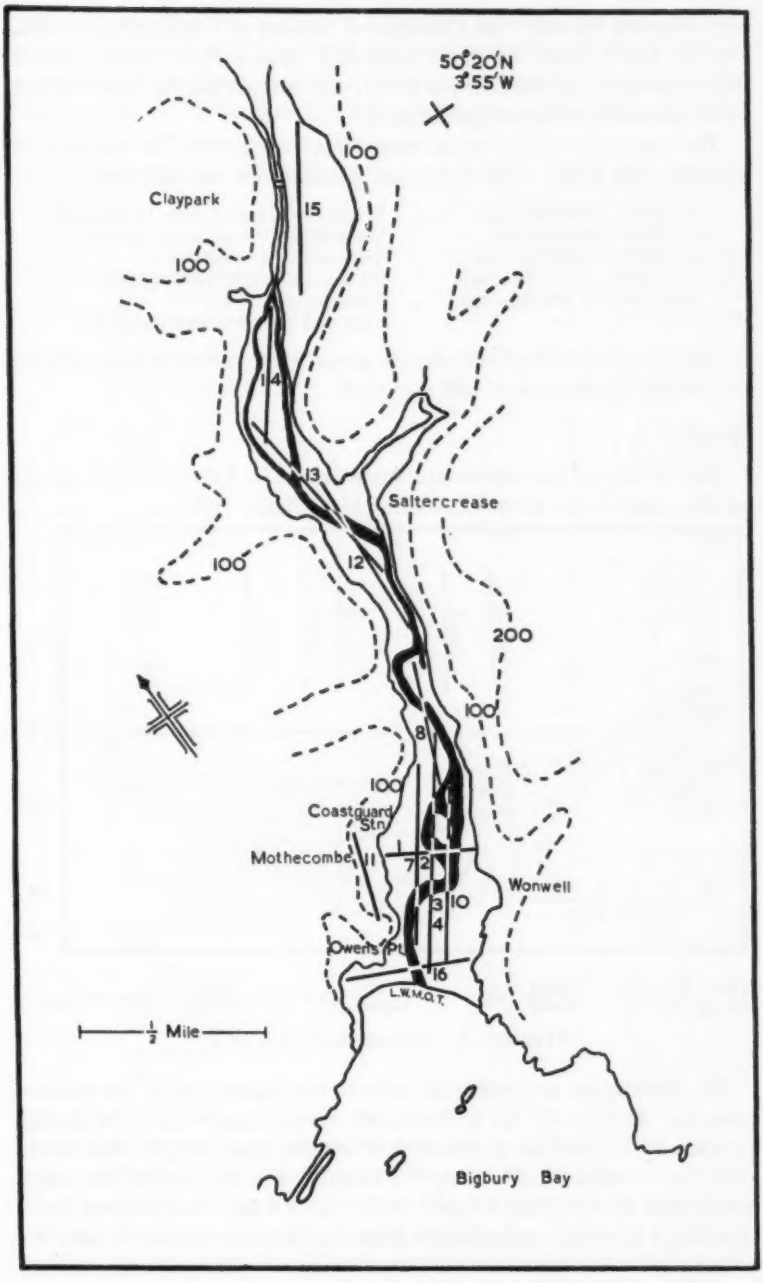
The seismic lines were surveyed wherever possible with a dumpy level from convenient bench marks. It was not possible to survey Lines 5, 6, and 8 in this way but in the cases of Lines 5 and 8, rough estimates of the heights were made by comparing the position of the tide at given times relative to known heights on other lines. Heights on the 6 in. O.S. map at Line 6 were assumed to be still approximately correct.

The explosive charges used in the two surveys were small on the whole since the waterlogged sand provided an excellent medium for propagation and the background level of microseisms remained low except during rain or snowstorms. Electric detonators were used up to 100 feet from the spread while charges of a few ounces of gelignite sufficed for more distant shots.

Erme Survey

Classification of Velocities

The problem of assigning velocities to particular formations was made very difficult by the fact that the strata changed exceedingly rapidly within short distances. In addition the dip is steep—40° towards the S.E.—and the seismic lines were inclined at various angles to the strike which is approximately E.N.E.–W.S.W. In this area the strata belong to the upper part of the Lower Devonian and the lower part of the Middle Devonian. There are a number of dolerite



TEXT-FIG. 1.—Erme Estuary with Seismic Lines.

sills exposed between the Coastguard Station and Saltercrease, while on the Cliffs south of the Coastguard Station thick bands of tuff are to be seen. At the time the survey was carried out the area had not been accurately mapped geologically.

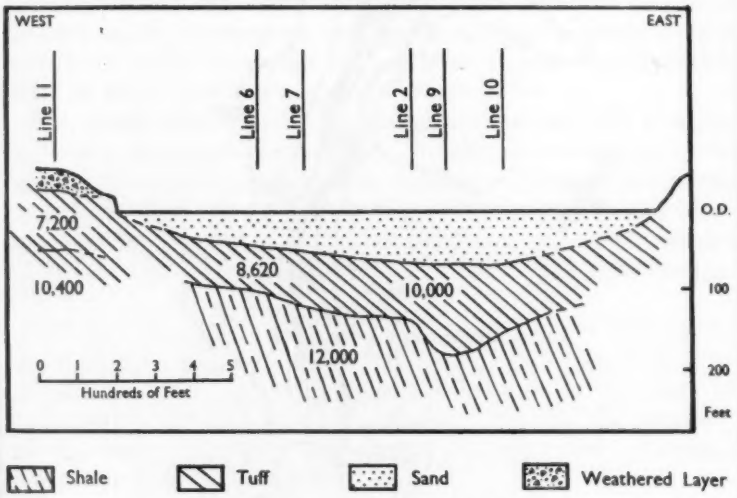
The measured velocities in many cases correspond to mixtures of distinct rock types. The following classification was adopted:—

1. 2,500–2,700 feet/sec. . Weathered layer (Lines 11 and 15)
2. 4,500–5,400 feet/sec. . Waterlogged sand, mud, gravel
3. 7,300–10,000 feet/sec. . Tuff and shale mixture
4. 12,000–13,500 feet/sec. . Shales, slates (Meadfoot age)
5. 14,700–15,500 feet/sec. . Staddon grit
   Grit and slate mixture (Line 14)

The wide variation of velocities in group 3 is intended to take account of various admixtures of tuff and shale.

Results

The results of the survey are summarized in Table I. Full details of the analysis are given elsewhere (McFarlane, 1953).



TEXT-FIG. 2.—Section through Line 1.

The thicknesses and velocities refer to the regions under the various spreads. At Line 10, for instance, the spread happened to be placed in such a way that the northern half overlay shale (12,000 feet/sec.), while the southern half overlay the Staddon grit bed (14,760 feet/sec.) which runs E.N.E. from Owen's Point. Line 5 has been omitted from Text-fig. 1 to avoid confusing the diagram, but it lay slightly S. and W. of Line 4. It was here that the deepest part of the buried rock channel was located at — 88 feet O.D.

From Text-fig. 2 it can be seen that the velocity of compressional waves in the rock lying between the sand and the shale decreases as one passes from the centre of the estuary to Line 11 on shore. The section (through Line 1) is inclined about 30° to the strike and it is

TABLE I

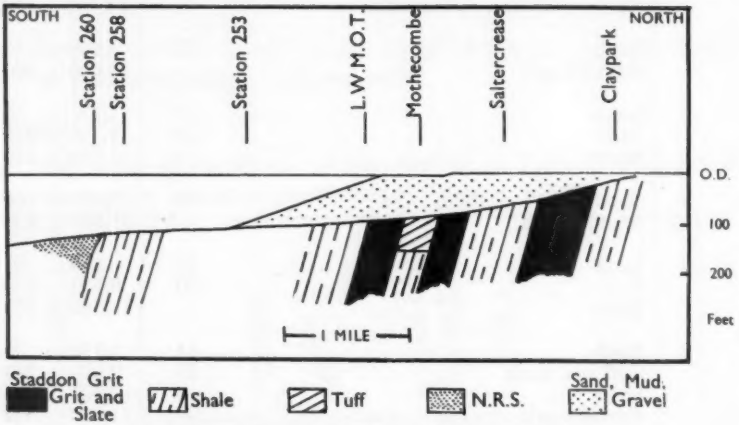
Line No.	Material	Thickness, ft.	Velocity, ft./sec.
2	Sand and gravel	69	4,800 ± 40
	Tuff and shale	97	10,900 ± 520
	Shale	—	12,700 ± 500
5	Sand	83	4,900 ± 50
	Staddon grit	—	15,000 ± 400
7	Sand	53	5,230 ± 30
	Tuff	82	8,330 ± 740
	Shale	—	12,050 ± 320
8	Sand	63	5,100 ± 160
	Staddon grit	—	15,000 ± 420
9	Sand	62	4,800 ± 30
	Tuff	120	9,500 ± 230
	Shale	—	11,540 ± 220
10	Sand	64	5,120 ± 20
	Tuff and shale	85	9,600 ± 300
	Shale	—	12,000 ± 450
	Staddon grit	—	14,760 ± 40
11	Weathered layer	22	2,490 ± 200
	Tuff	79	7,230 ± 210
	Tuff and shale	—	10,380 ± 680
12	Sand and mud	74	4,970 ± 260
	Slate (possible bands of dolerite)	—	13,230 ± 110
13	Sand and mud	44	4,600 ± 60
	Slate	—	13,000 ± 200
14	Mud	47	4,290 ± 280
	Slate and grit	—	15,400 ± 360
15	Weathered layer	27	2,600 ± 90
	Slate	—	13,100 ± 290

clear that the strata are changing slowly in texture (more tuff) as one goes northwards. It is important to observe that the form of Text-fig. 2 is a projection of the true structure and that there is no question of folding along an axis perpendicular to Line 1.

The basin lying N.E. of Mothecombe is bounded on the north and on the south by thick bands of Staddon grit (Text-fig. 3). There is

some seismic evidence that the northern grit band is present under spread 2 at a depth of about 600 feet and that it may in fact be joined to the southern band at about that depth.

The longitudinal profile of the Erme estuary is shown in Text-fig. 3. The seismic profile has been continued out to sea to include three sea-bed sampling stations. Samples were collected from these points in the course of a survey carried out to delineate the junction of the Devonian and Permian, and to investigate the contours of the sea-bed off the Erme and Avon. The geological results are described by Hill and King (1953). Echo-sounding along lines parallel to the coast off the Erme



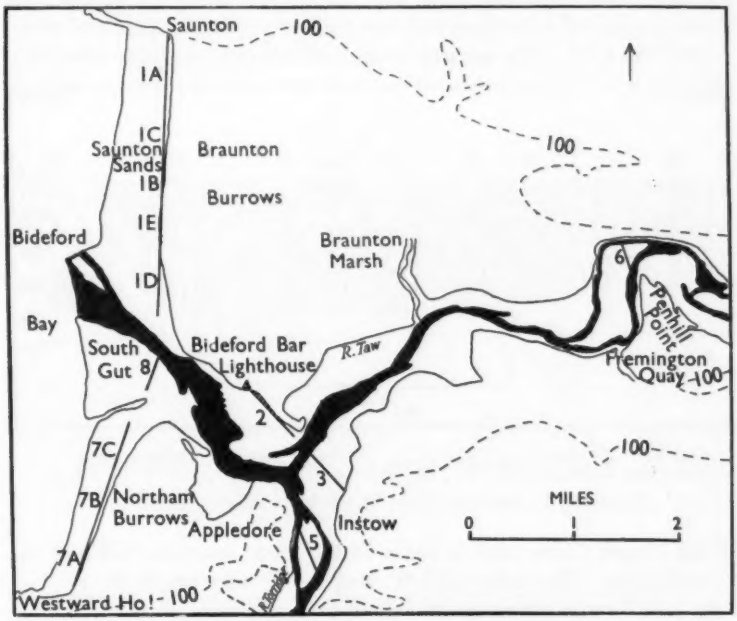
TEXT-FIG. 3.—Profile through Erme Estuary.

and Avon at distances greater than one mile from shore, failed to reveal any sign of channels on the sea floor which could have been eroded by these rivers during a period of low sea-level. Since the tides have a strong scouring action, the rocky floor is only lightly covered with sand and there is no possibility that channels filled with debris could exist.

The profile drawn in Text-fig. 3 is a smoothed version of the one obtained by plotting the results from Table I. It is impossible to say whether or not all the measured depths ought to lie on one smooth curve or not. There may be one or more buried " knick points ". It is interesting to note that the curve of Text-fig. 3 can be fitted very well to one limb of the hyperbola $(y + 197)(x + 5{\cdot}6) = 633{\cdot}07$, where y is in feet above O.D. and x is in miles. The base level is — 197 feet O.D., and the distance from L.W.M.O.T. to where the ancient river assumed a gradient of 5 feet/mile (the present river's gradient in the tidal region) is 5·6 miles, the depth there being — 141 feet O.D. It appears from this approximation that the old river graded to a level between 140 feet and 150 feet below present sea-level.

The facts that the sides of the ancient valley were found to be steep, and the bottom comparatively flat, suggest that a lengthy period of marine erosion was a contributory factor in the development of the valley. The sections across the estuaries of Plymouth given by Worth show similar features.

The existence of New Red Sandstone off-shore is an important feature, for if the sea-level had fallen by as much as 200 feet for any length of time the rivers of S. Devon would have cut back into the soft rock and remains of the channels would be detectable to-day. At the time these flat-bottomed channels were formed the sea shore could not have been far off.



TEXT-FIG. 4.—Taw-Torridge Estuary with Seismic Lines.

TAW–TORRIDGE SURVEY

Classification of Velocities

The seismic velocities were classified using the known geology of the area (Hamling, 1910), as follows:—

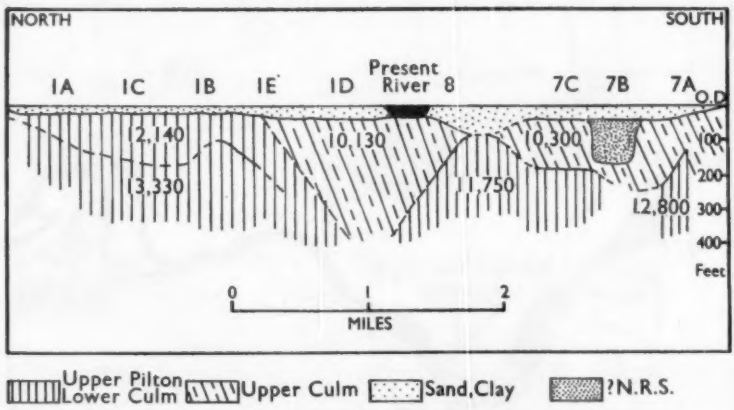
1. 9,200–10,330 feet/sec. . Upper Culm Measures (Flaggy silts and mudstones)
2. 11,700–13,800 feet/sec. . Lower Culm Measures Upper Pilton Beds (shales)[1]

[1] Mr. R. Goldring, Geology Department, University of Bristol, has pointed out to me that the velocities of the order of 13,300 feet/sec. may refer to Lower Pilton Beds under the northern part of Saunton Sands.

Results

The section from Saunton to Westward Ho ! which is shown in Text-fig. 5, was obtained in nine parts and is complete save for the region where the present river flows at Low Tide and in the part between Line 8 and Line 7C which was too waterlogged and uneven for measurements to be made.

From Text-fig. 5 it will be seen that on the whole the thickness of sand and clay remains small, but that under Line 8 the north bank of the ancient river channel was located. The thickness of recent sediment increases from 32 feet at the northern end to 79 feet at the southern end. It seems likely that the deepest point of the old rock channel must lie a few hundred feet further south at a depth of about — 100 feet O.D. The ancient river evidently cut away the softer silts



TEXT-FIG. 5.—Section from Saunton to Westward Ho!.

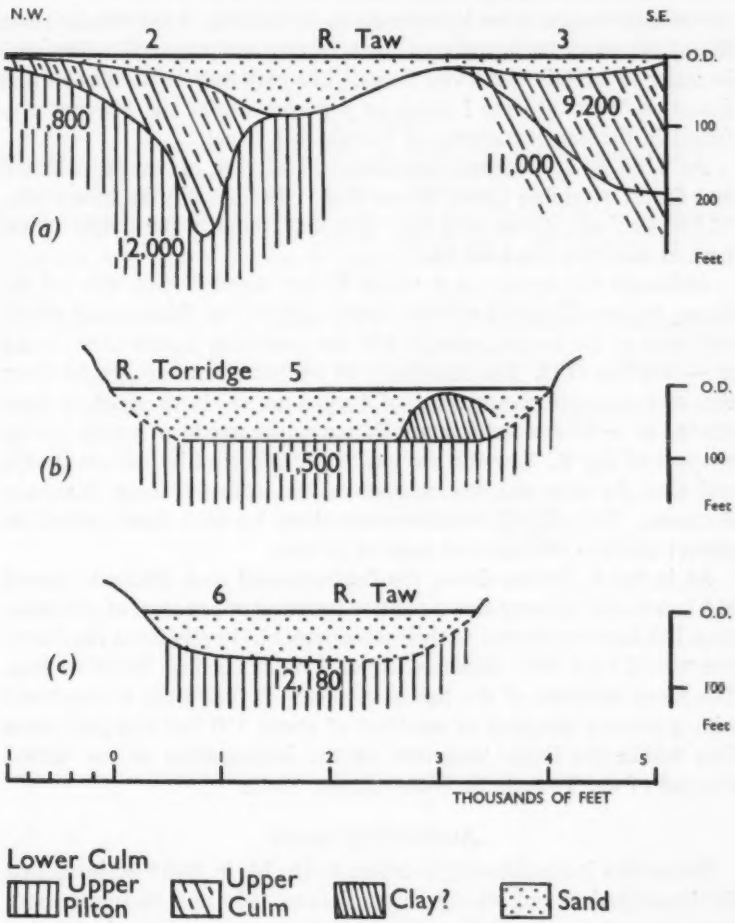
of the Upper Culm until it came to the more resistant rocks of the Lower Culm. (The strike is E.–W. and the dip very nearly 90°.)

At Line 7B the seismic results infer a trough of rock, of compressional wave velocity 8,600 feet/sec. apparently lying in Upper Culm Measures. One interpretation of this feature is that it is an inlier of Permian sandstone.[1] There is an exposure of Permian sandstone on the cliffs on the south side of Bideford Bay. On the other hand the " trough " may simply be the weathered zone of a small anticline which has been mapped further east.[2]

[1] Borings have been made on the beach near Line 7B by Dr. Alan Stuart, Geology Department, University College, Exeter, and by Mr. R. J. Hookway of the Devon County Council. Although their boring tools came up stained red, the holes caved in before samples could be examined. (Private communication.)

[2] The author is indebted to Dr. J. E. Prentice, Geology Department, King's College, London, for this information.

The suggestion that the " trough " is an inlier of Permian sandstone implies that the rocks under Bideford Bay may be New Red. Unfortunately it has not been possible to obtain samples through the thick coating of sand on the sea floor. This covering of sand which may be



TEXT-FIG. 6.—(*a*) Bideford Bar Lighthouse to Instow. (*b*) Newquay Ridge (Line 5). (*c*) Penhill Point (Line 6).

20 feet thick a mile or so from shore, has also made it impossible to investigate the rock floor by echo-sounding.

The section from Bideford Bay Lighthouse to Instow is shown in Text-fig. 6 (*a*). The principal features are that the buried channel lies at a depth of — 85 feet O.D. and that the fold in the Lower Culm

seen in Text-fig. 5 seems to have continued through this point. Under Line 3 there appears at least from a seismic point of view to be a subdivision of the Upper Culm though this may be due to weathering.

The shape of the buried channels has been determined satisfactorily at Line 5 in the Torridge and at Line 6 in the Taw. In the former case the seismic results were interpreted as in Text-fig. 6 (*b*) where it was found necessary to postulate a bank of clay (velocity 6,000 feet/sec.) in order to explain the travel times. The clay may be similar to that found on Westward Ho ! beach or it may resemble the Pliocene clay found in the neighbourhood of Fremington Quay.

At Line 6, a maximum thickness of 62 feet of recent sediment was found overlying Upper Pilton Beds. The velocity in these rocks, 12,180 feet/sec., agrees very well with that found in the Upper Pilton beds at Saunton (Text-fig. 5).

Although the survey as a whole is less detailed than that of the Erme, the results give a reliable upper limit to the thickness of recent sediment at the mouth, namely 100 feet overlying Lower Culm rocks at — 100 feet O.D. The confluence of the two rivers was not far from that of the present rivers, north of Appledore, and both appear to have graded to — 85 feet O.D. there. It is a noticeable fact that the buried channel of the R. Taw for the most part underlies its present course and that the river did not excavate a deep channel under Braunton Burrows. The seismic measurements along Saunton Sands reveal an almost uniform thickness of sand of 30 feet.

As in the S. Devon rivers, the flat-bottomed rock channels (found at Lines 5 and 6) imply that a relative lowering of sea-level of not more than 150 feet contributed to their development. In this event the shoreline would have been displaced about 8 miles out into Bideford Bay. The mean gradient of the buried channels (7 feet/mile) is consistent with a relative lowering of sea-level of about 150 feet and this value falls within the limits suggested by the investigation of the buried channel of the Tawe in S. Wales (Jones, 1942).

Acknowledgments

The author is considerably indebted to Dr. M. N. Hill who instigated the investigation and who gave continuous help and encouragement throughout the work, and to Mr. M. I. Scott, who designed and constructed the amplifiers used in the seismic experiments and who assisted in the Erme survey.

Acknowledgment is made to Commander and the Hon. Mrs. White for permission to survey the Erme estuary; to the Christie Estates, Ltd., for permission to survey the Taw and Torridge estuaries; to the Director of the M.B.A. Laboratory, Plymouth, for granting the use of M.V. *Sabella* for the sea-bed sampling; to the Captain and crew of

Sabella for their expert handling of the ship and core sampler; and to the Commanding Officer, Amphibious Warfare Establishment, Fremington, for making available a DUKW for the Taw–Torridge experiments.

The author wishes also to acknowledge financial aid provided by the Department of Scientific and Industrial Research, and maintenance grants from the Carnegie Trust, the Cross Trust, and from the University of St. Andrews.

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CORRESPONDENCE

MAGMATIC AND AMYGDALOIDAL PLAGIOCLASES

SIR,—The closing paragraph of Mr. Le Bas' paper on the above subject (*Geol. Mag.*, xcii, 1955, 291–296) reveals a fundamental misapprehension regarding feldspathic bodies, within some of the Slieve Gullion rocks, interpreted by me as recrystallized amygdales that originally contained zeolites (*Trans. Roy. Soc. Edin.*, lxii, 1951, 99–102, 123–124). These bodies are not single large crystals as Mr. Le Bas supposes, but, as stated in my paper (p. 101), consist of " intergrowths of lime-soda feldspar ". The " white gabbros " containing them form the upper portions of layers of feldspar-phyric dolerite characterized by macroscopic phenocrysts of plagioclase, some of which are themselves composite intergrowths. The rocks concerned are in fact members of the " porphyritic central magma-type " of Thomas and Bailey, and Mr. Le Bas is correct in saying that the large crystals of plagioclase represent original phenocrysts. Presumably, however, Mr. Le Bas has been labouring under the entirely mistaken impression that I supposed these plagioclase phenocrysts to be recrystallized amygdales. Mr. Le Bas' conclusions neither add to nor subtract from my inferences from the Slieve Gullion rocks.

It is, however, desirable that a criterion be established whereby plagioclase resulting from the metamorphism of zeolite-filled amygdales may be distinguished from the initial plagioclase of basalts that have undergone the same limited degree of metamorphism. It was previously my intention to attempt to find such a criterion by reference to the relative frequency of occurrence of twins of various types, paying due attention to the composition of the plagioclases concerned. I was encouraged in this intention by the positive results already obtained by Dr. M. Gorai (*Journ. Geol. Soc., Japan*, lvi, 1950, 149–156) who applied this method to the problem of distinguishing magmatic from metamorphic rocks. The task is an onerous one involving hundreds of measurements with the universal stage on suitably chosen material, including the basalts of metamorphic terraines. If Mr. Le Bas will now undertake this investigation he will not only make an important contribution to petrology, but amply atone for his misrepresentation of my work.

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5th September, 1955.

AGE OF THE WEALDEN IN NORTH-WESTERN EUROPE

SIR,—May I express my appreciation of Professor P. Allen's recent discussion of the age of the Wealden (*Geol. Mag.*, xcii, 1955, 265–281).

The problem is clearly stated but, since very little of the relative palaeontology has yet been published, Allen's conclusions must in many instances remain highly speculative. A particular case is the correlation of the English and German Wealden. The detailed succession of ostracod faunas in S.E. England is now fairly well known but more information is being obtained daily. In Germany the fauna is poorer and the amount of material available for study is relatively small. Nevertheless, having examined ostracod faunas from both countries I have little doubt about the correct correlation of the Wealden. Wolburg's statement that the German " Wealden 4 " is the equivalent of the uppermost Wealden of England as exposed at Berwick cannot be substantiated (Wolburg, J., 1949, " Zur Frage des Alters der obersten Wealdenschichten in England," *Neues. Jahrb. f. Min.*, Abt. B., vii, 193; and 1950, " Vergleichende stratigraphische Untersuchungen der brackisch limnischen Ablagerungen Europas an der Wende Jura-Kreide," *Geol. Landesanst., Geol. Jahrb. f. 1943–8*, lxiv, 159).

The species he collected from Berwick and identified as *Gomphocythere*

berwickensis Martin is, in fact, the juvenile of the well known *Metacypris fittoni* (Mantell) which although common in the uppermost Wealden in the Weald and in the Isle of Wight, nevertheless is present at intervals and in abundance in the middle part of the Hastings Beds. Furthermore, none of the species typical of the Weald Clay in England such as *Cypridea clavata* Anderson, *C. dorsispinata* (Anderson), *Cypridea tuberculata* (J. de C. Sowerby), and " *Cypris* " *henfieldensis* Anderson have yet been found in the German Wealden.

Comparing the ostracod faunas of the English Wealden with those found in the Thören, Rodewald, Adorf, Itterbreck, and other German borings the correlation appears to be:—

England—Weald Clay	*Germany*—Marine strata
Hastings Beds	Wealden 3–6
Upper Purbeck	Wealden 2
Middle Purbeck (Part)	Wealden 1

The base of Wealden 1 in N. Germany appears to be at about the horizon of the " Cinder Bed " of the English Middle Purbeck.

F. W. Anderson.

Geological Survey and Museum,
Exhibition Road,
London, S.W. 7.
20th September, 1955.

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